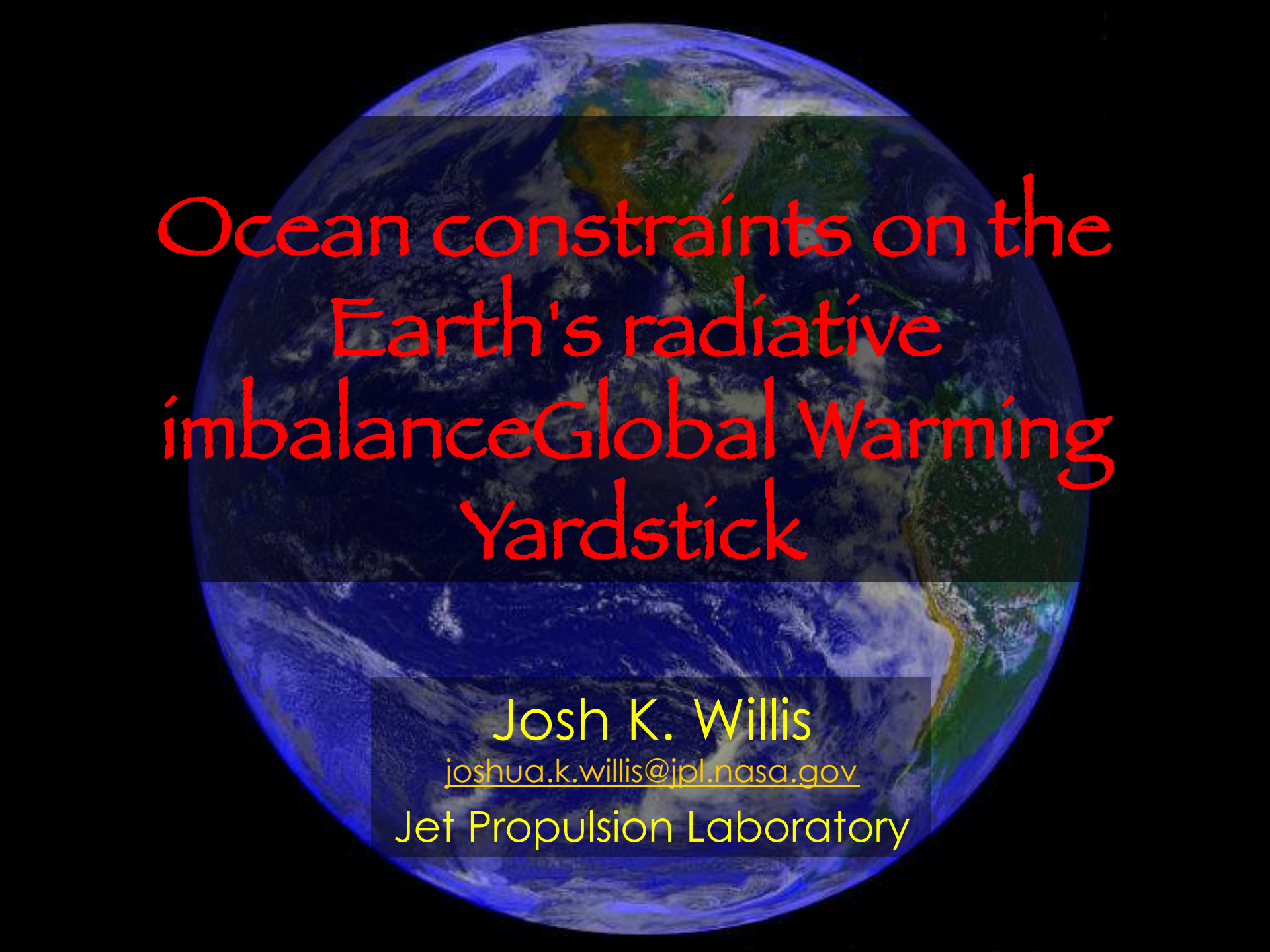
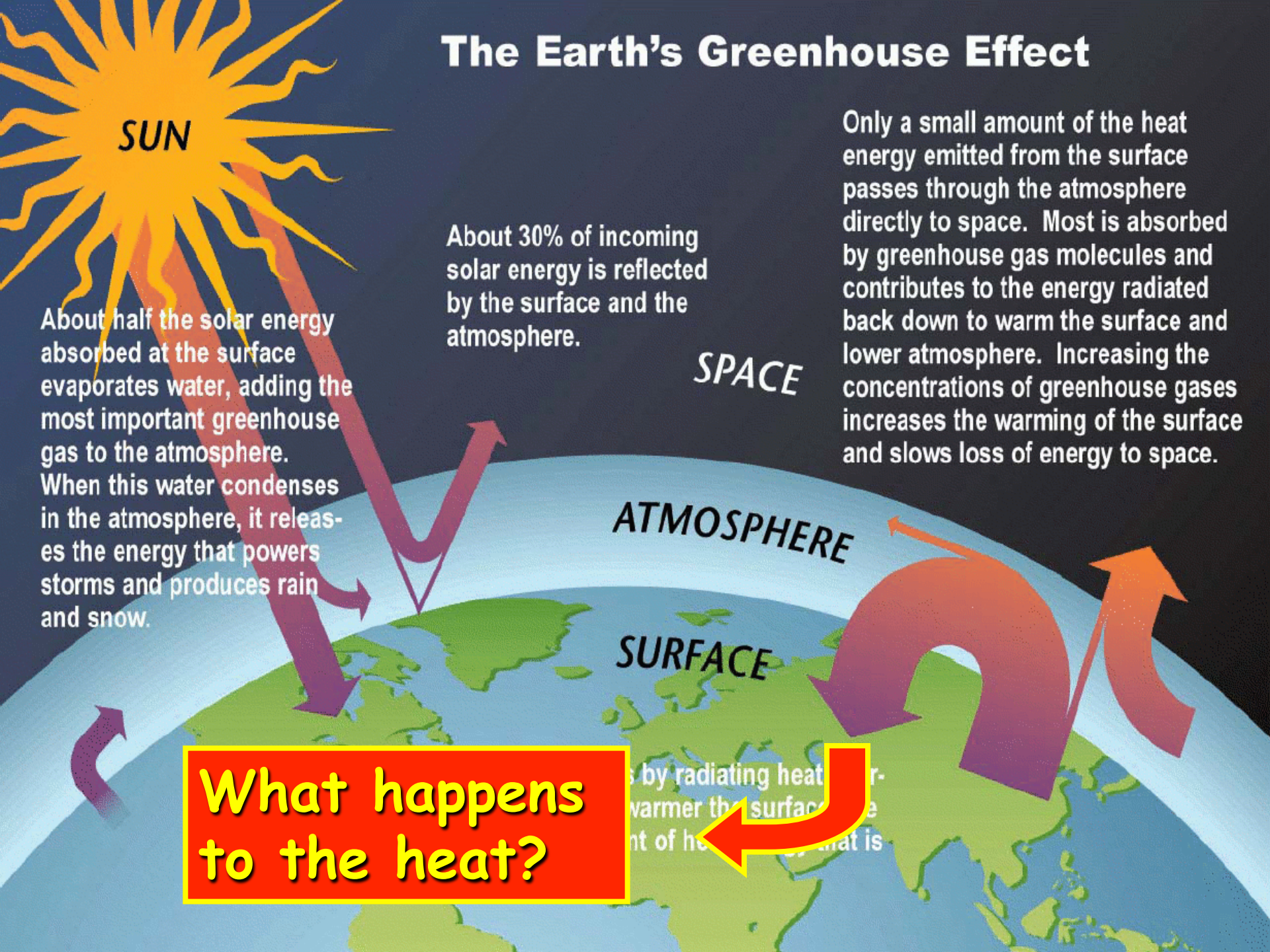
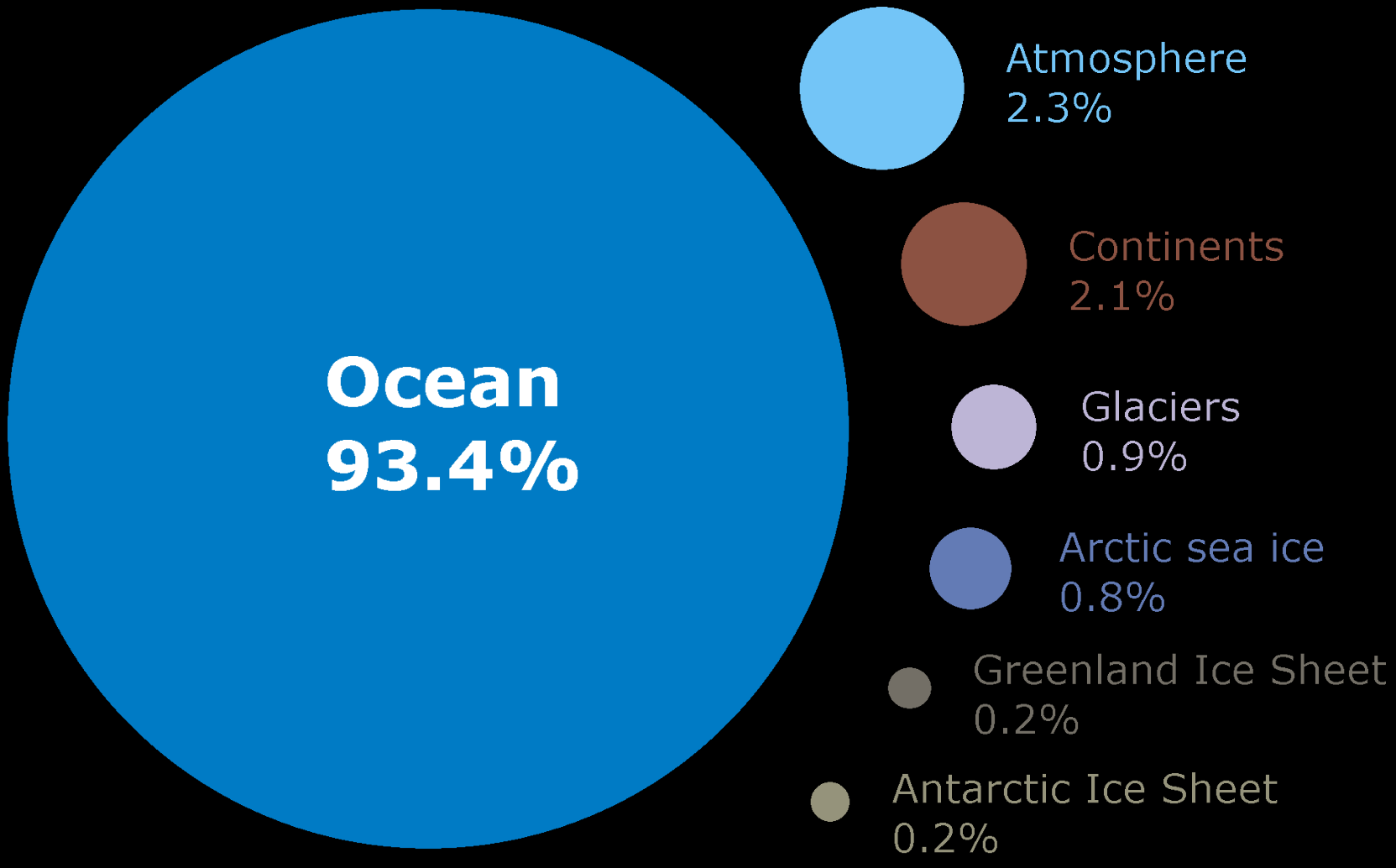


Ocean constraints on the Earth's radiative imbalanceGlobal Warming Yardstick

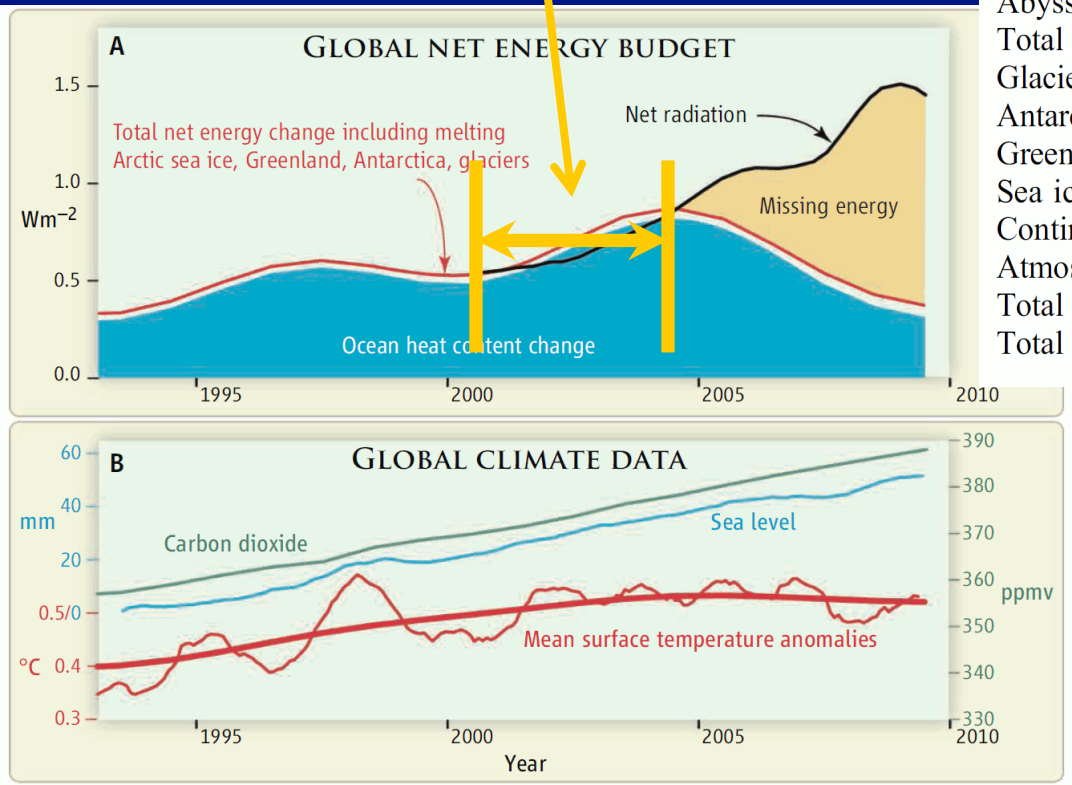
Josh K. Willis
joshua.k.willis@jpl.nasa.gov
Jet Propulsion Laboratory


The Earth's Greenhouse Effect
SUN
About half the solar energy absorbed at the surface evaporates water, adding the most important greenhouse gas to the atmosphere. When this water condenses in the atmosphere, it releases the energy that powers storms and produces rain and snow.
About 30% of incoming solar energy is reflected by the surface and the atmosphere.
SPACE
Only a small amount of the heat energy emitted from the surface passes through the atmosphere directly to space. Most is absorbed by greenhouse gas molecules and contributes to the energy radiated back down to warm the surface and lower atmosphere. Increasing the concentrations of greenhouse gases increases the warming of the surface and slows loss of energy to space.
ATMOSPHERE
SURFACE
What happens to the heat?

Where is global warming going?



Assumed 0.9 W/m² based on comparison with biased XBT-based estimates of OHC



Where does the energy go? (**A**) Estimated rates of change of global energy. The curves are heavily smoothed and somewhat simplified. From 1992 to 2003, the decadal ocean heat content changes (*10*) (blue), along

Trenberth & Fasullo, *Science*, 2010

Church et al., *GRL*, 2011

Table 2. The Earth's Heat Budget[a] (X 10^{21} J)

Component	1972–2008	1993–2008
Shallow ocean (0–700m)	112.6	45.9
Deep ocean (700–3000m)	49.7	20.7
Abyssal ocean (3000m-bottom)	30.7	12.8
Total ocean storage	**193.0**[b]	**79.4**
Glaciers (Latent only)	3.0	1.7
Antarctica (Latent only)	1.4	0.8
Greenland (Latent only)	0.7	0.6
Sea ice	2.5	1.0
Continents	4.7	2.0
Atmosphere	2.0	1.2
Total other storage	**14.2**	**7.3**
Total storage	**207.2**	**86.7**

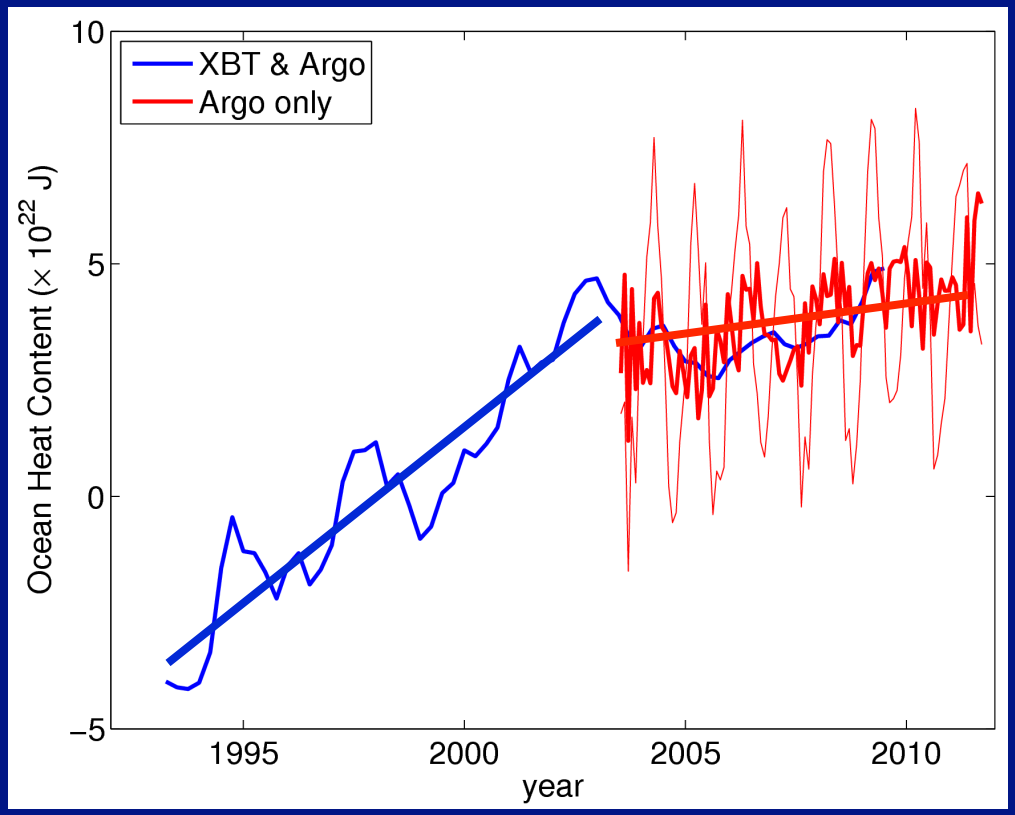
0.36 W/m²

0.36 W/m²

In light of update, is there still any "missing energy"?

Ocean Warming in the past two decades

0-750 m Ocean Heat Content

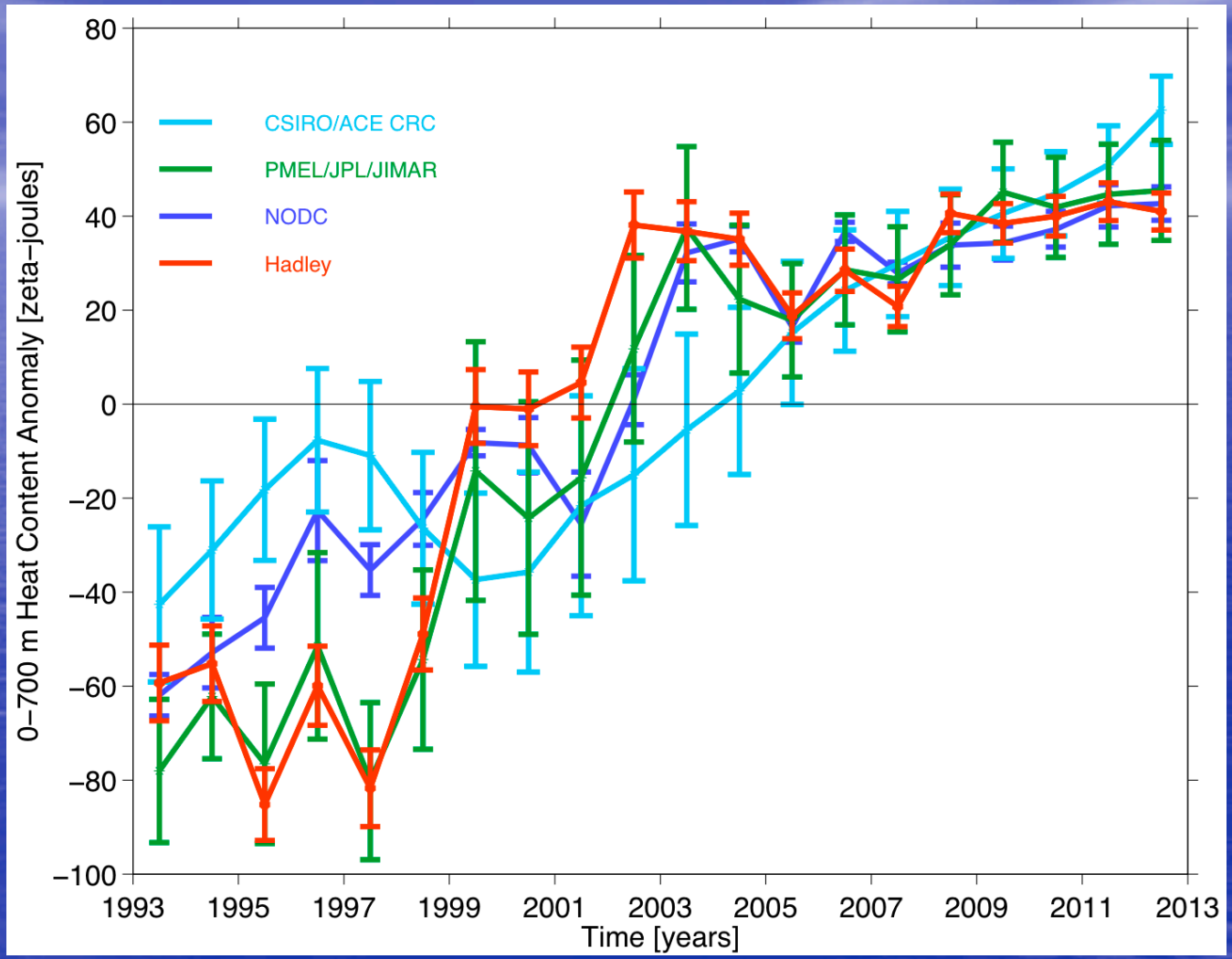


Bias-corrected XBTs included in estimate since 1993

Was there a slowdown in ocean warming during the 2000s?

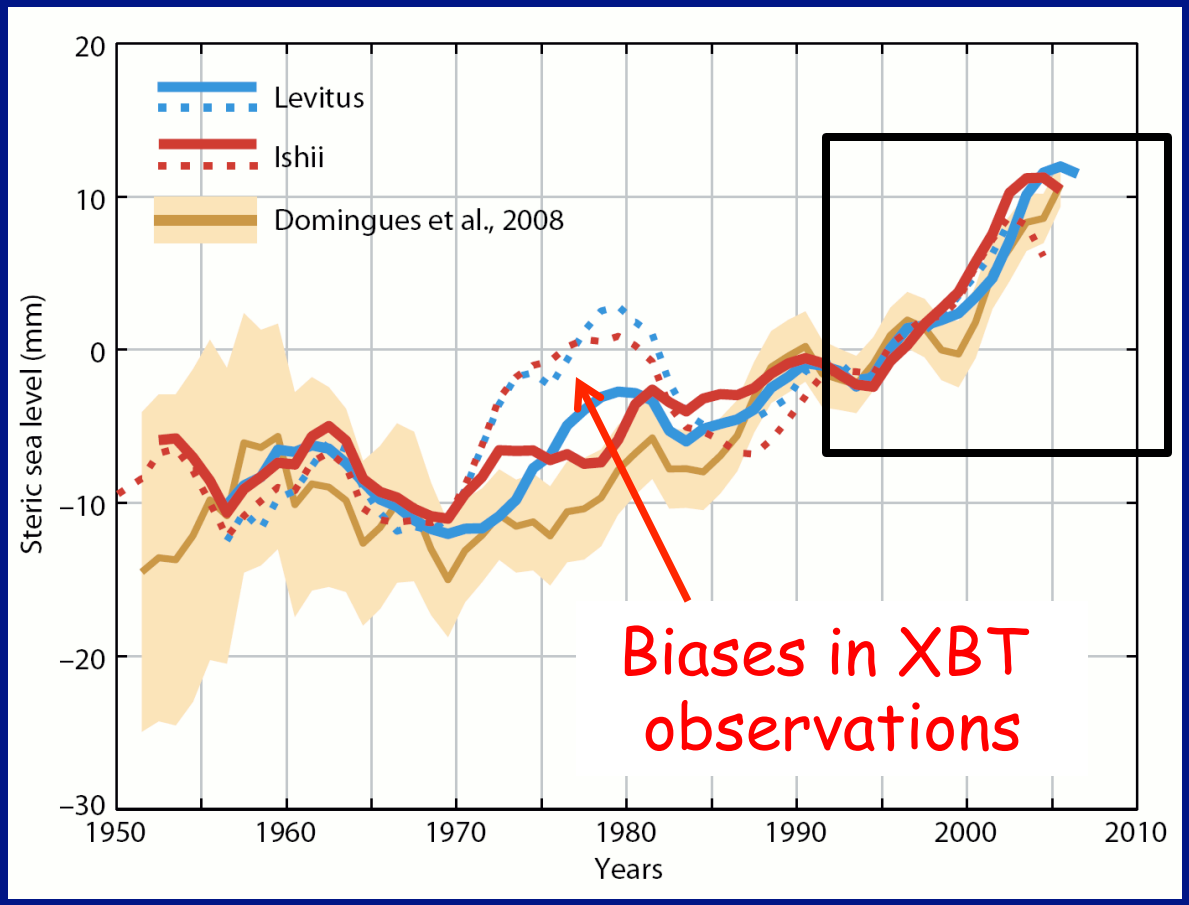
Upper Ocean Heat Content Estimates

- Upper Ocean Heat Content Anomaly estimates from four international groups demonstrate
  - Agreement on large heat gain of the upper ocean over decadal time-scales
  - Larger uncertainty in 1990s owing to variations in XBT bias corrections
  - Increased certainty of estimates post-2004 (Argo)



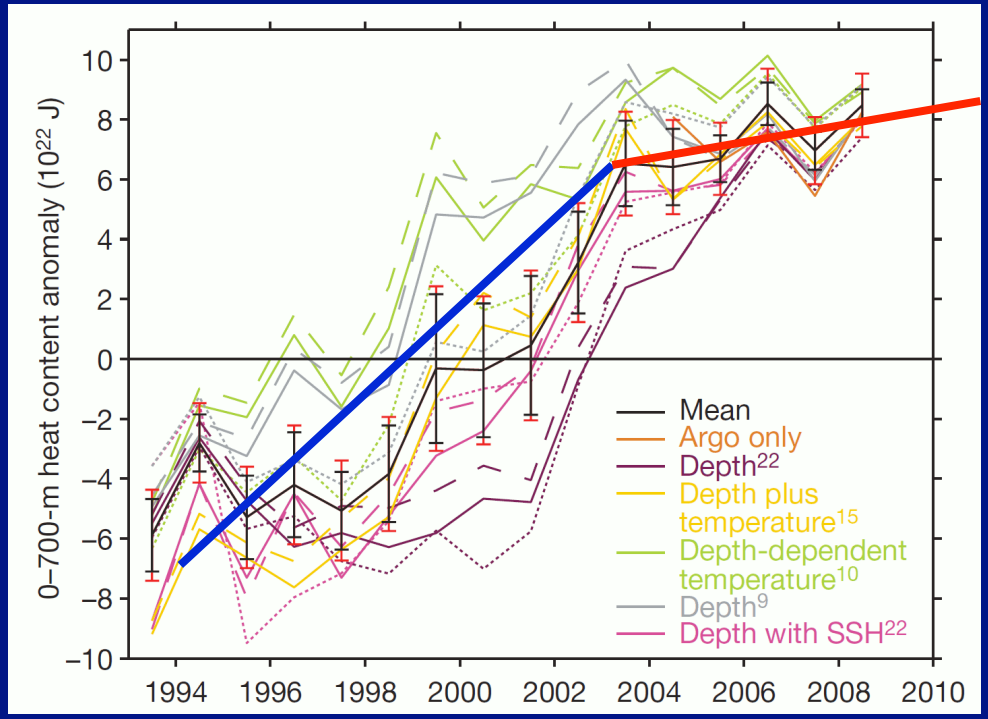
Johnson et al. (2013)
Global Oceans: Heat Content
in *State of the Climate in 2012*
Bull. Am. Met. Soc., **94**, *8*, S50-S53

Correcting the Historical Record of Thermosteric Sea Level Rise



From Johnson & Wijffels, *Oceanography*, 2011

Global Sea Level Budget
Ocean Warming



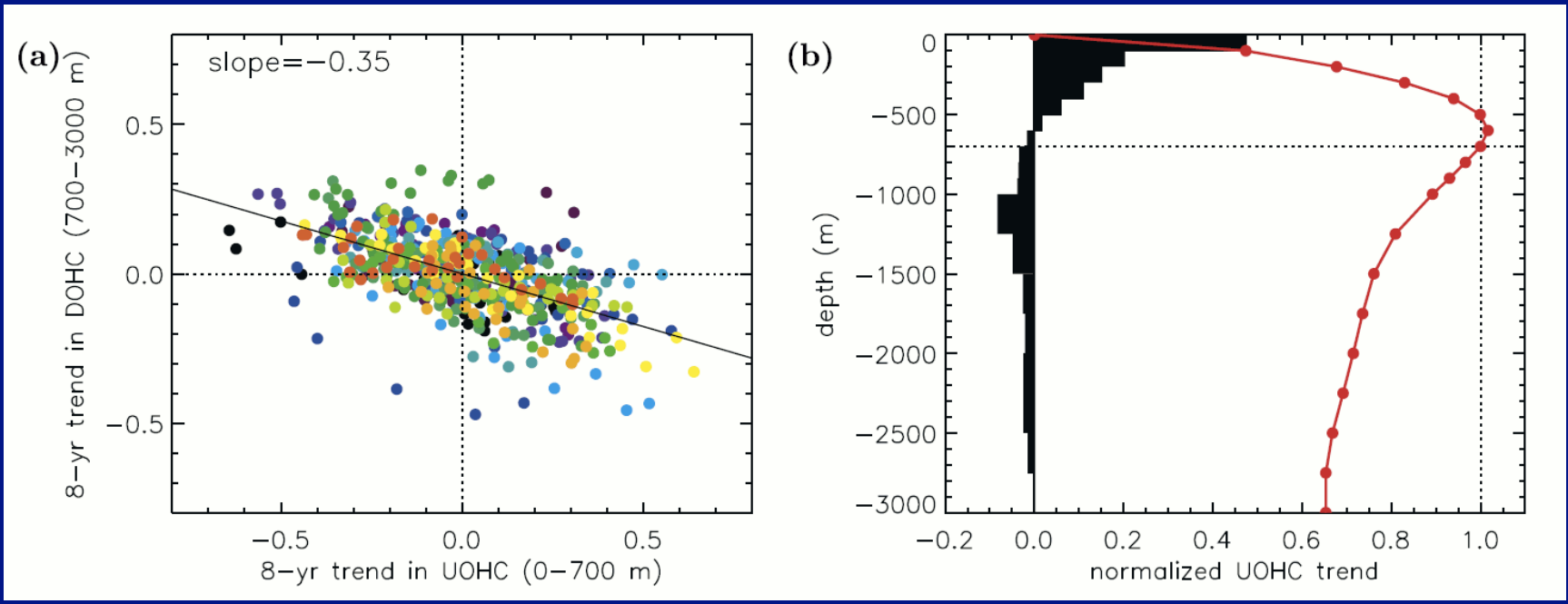
Different approaches to correcting XBT biases yield different results:
XBT biases remain!

Given the uncertainties, perhaps the "slowdown" is not robust…

From Lyman et al., *Nature*, 2010

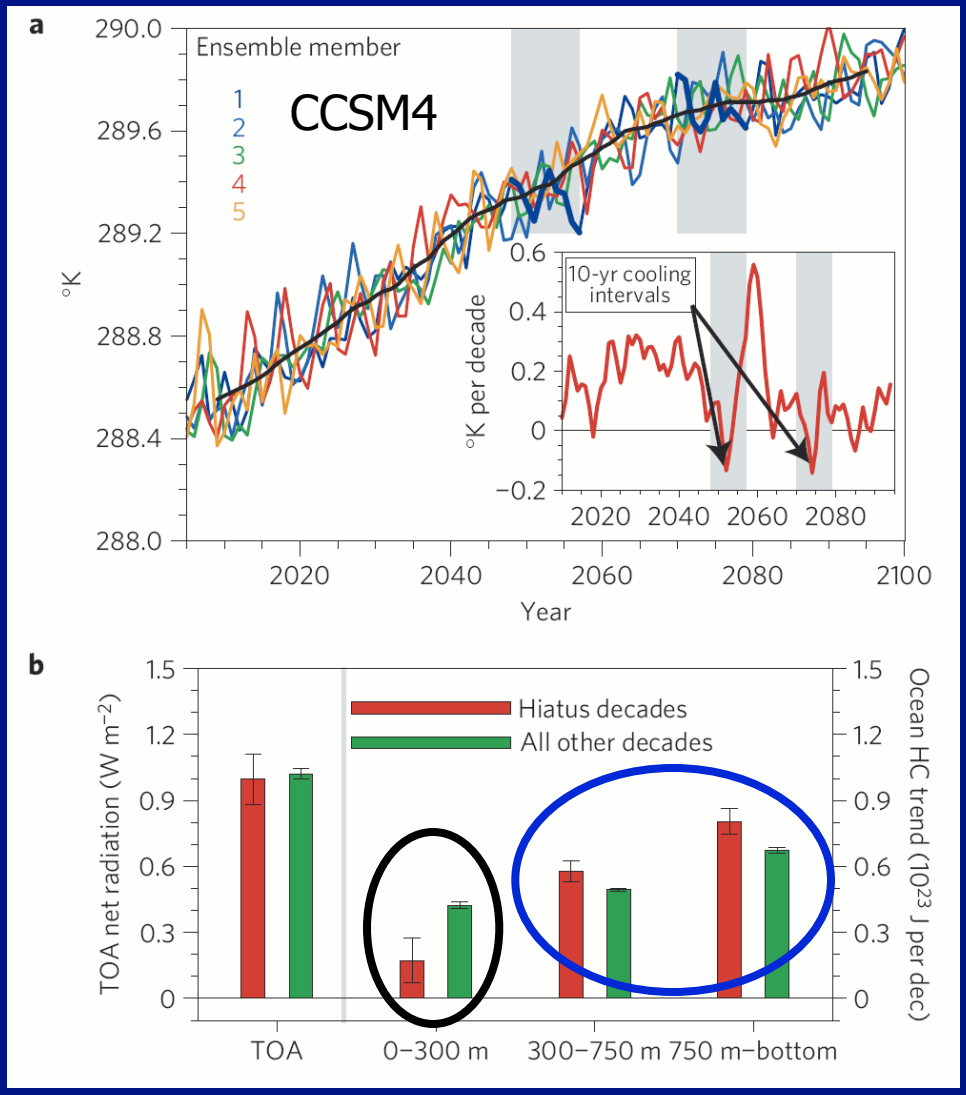
Upper Ocean vs Deep Ocean

Anti-correlation between upper & deep OHC in ECHAM5



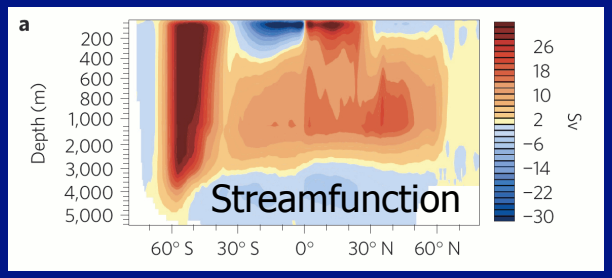
From Katsman van Oldenborgh, *GRL*, 2011

Deep Warming

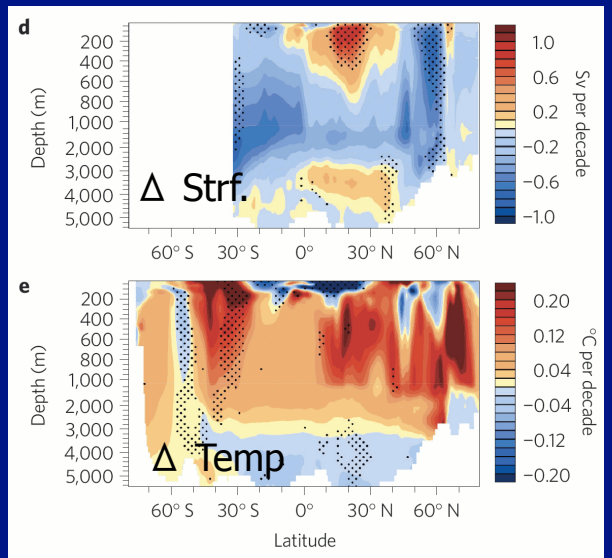


From Meehl et al., *Nature Clim. Ch.*, 2011

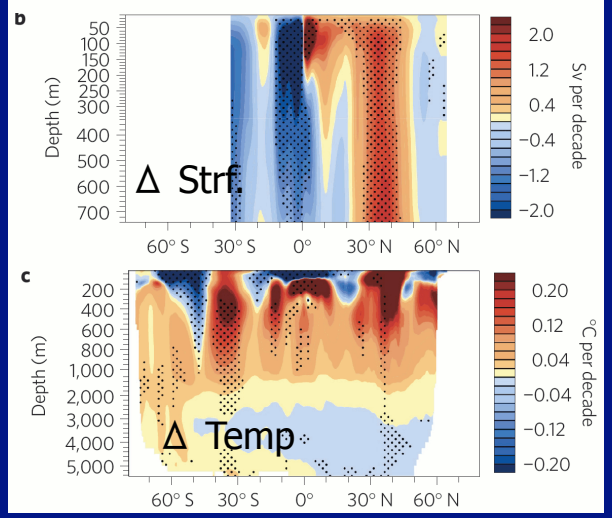
Global



Atlantic

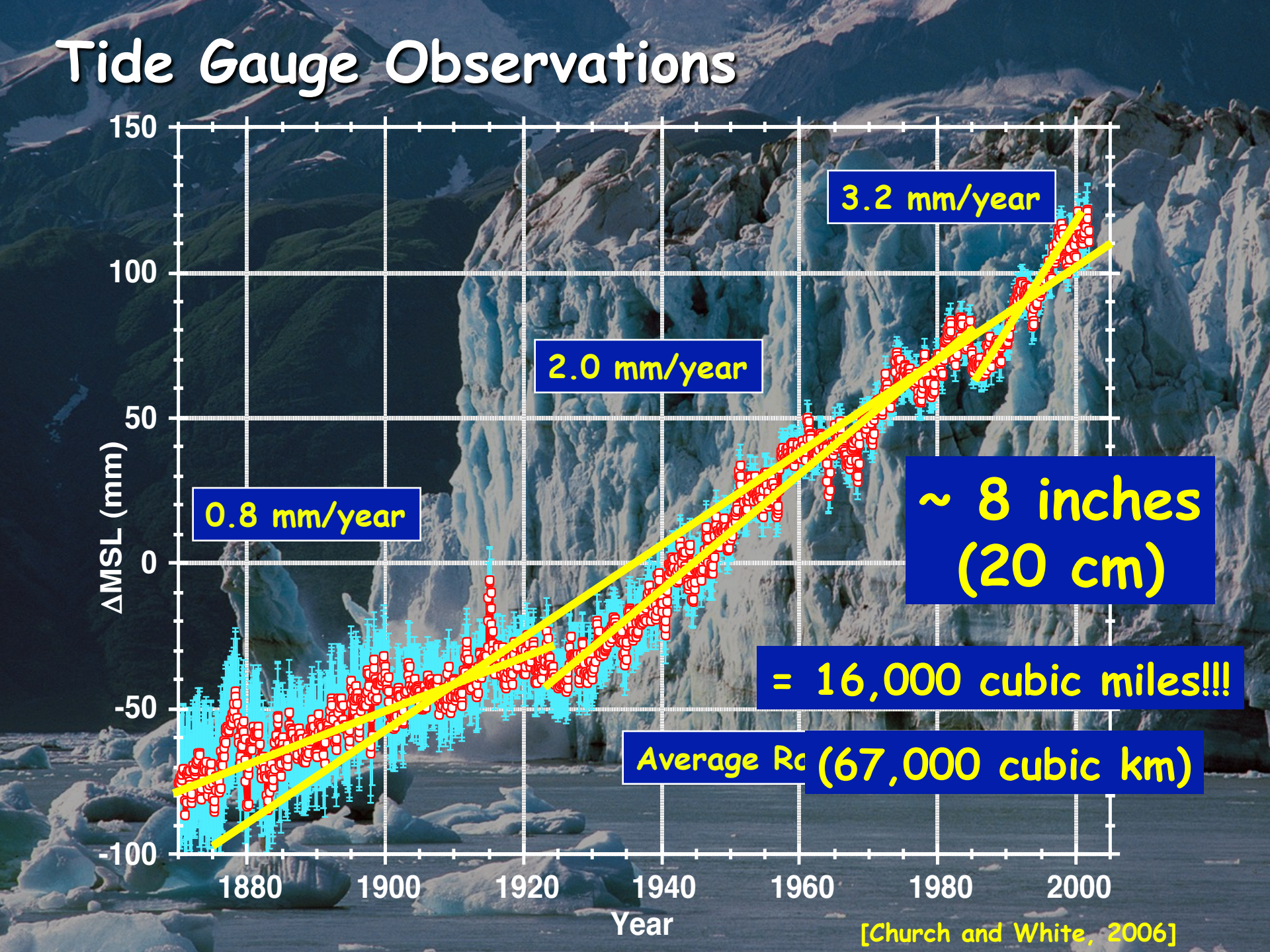


Pacific

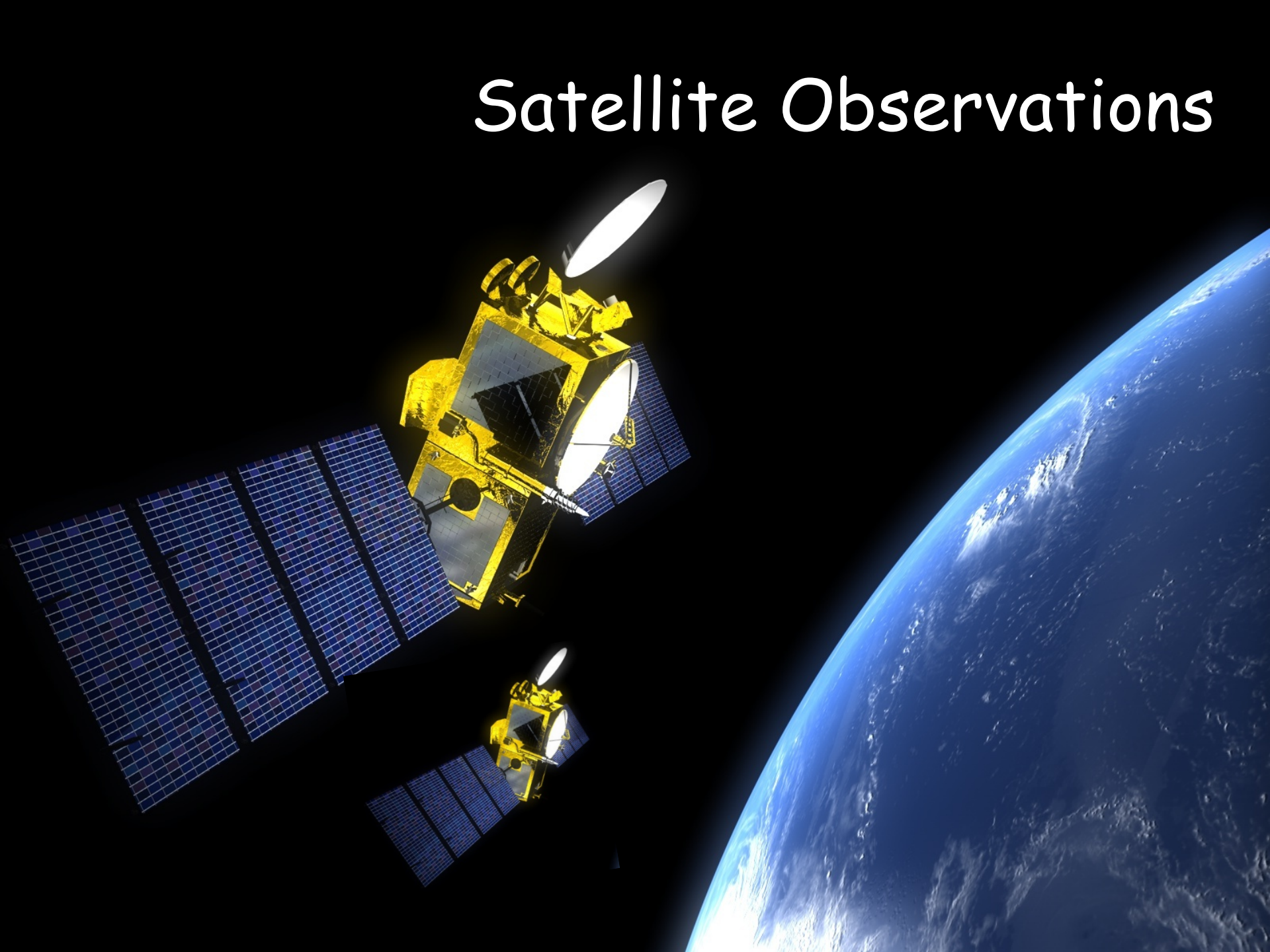


Sea Level Rise and the Energy Balance

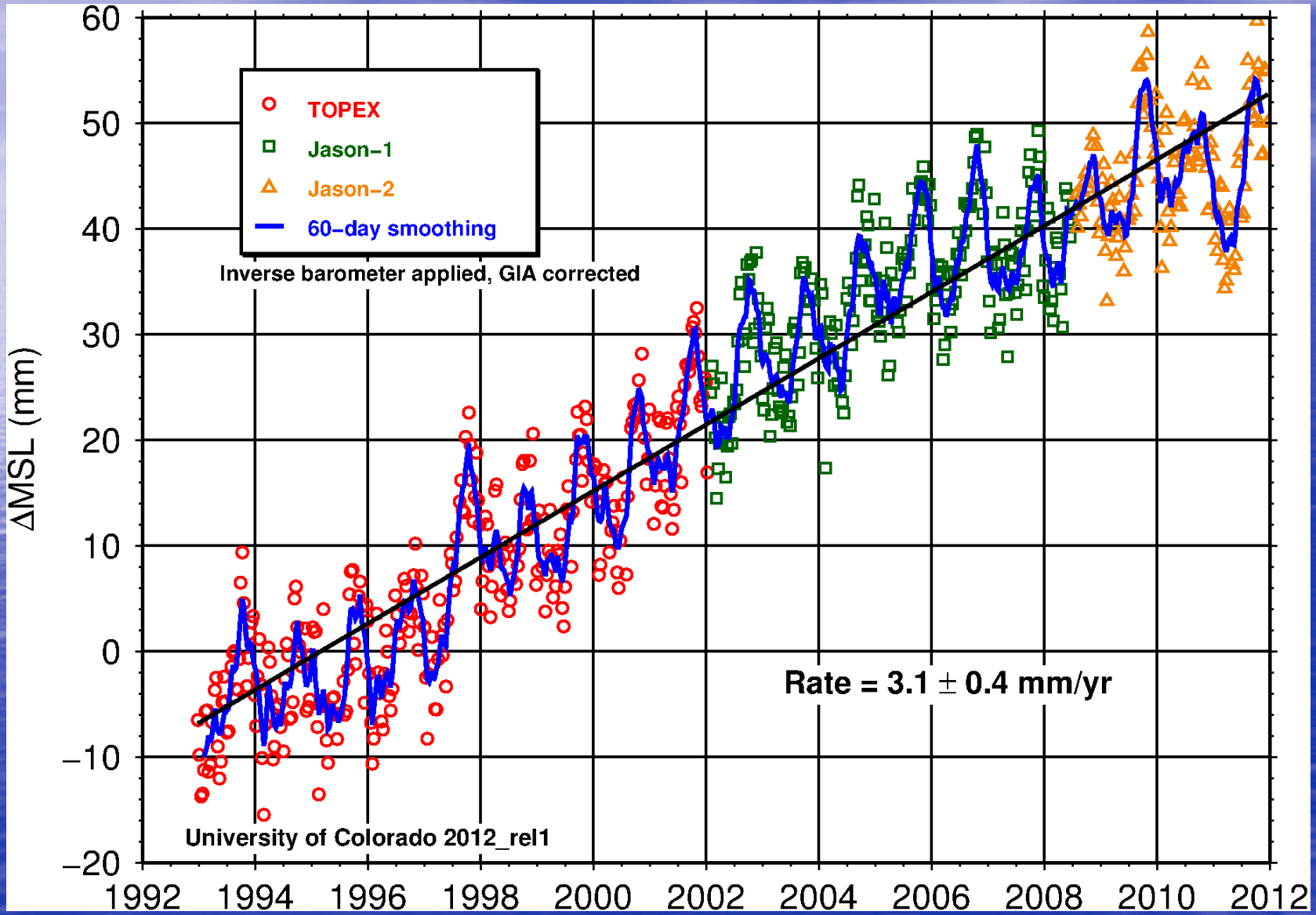
Tide Gauge Observations



Satellite Observations



Sea Level Rise from Satellites

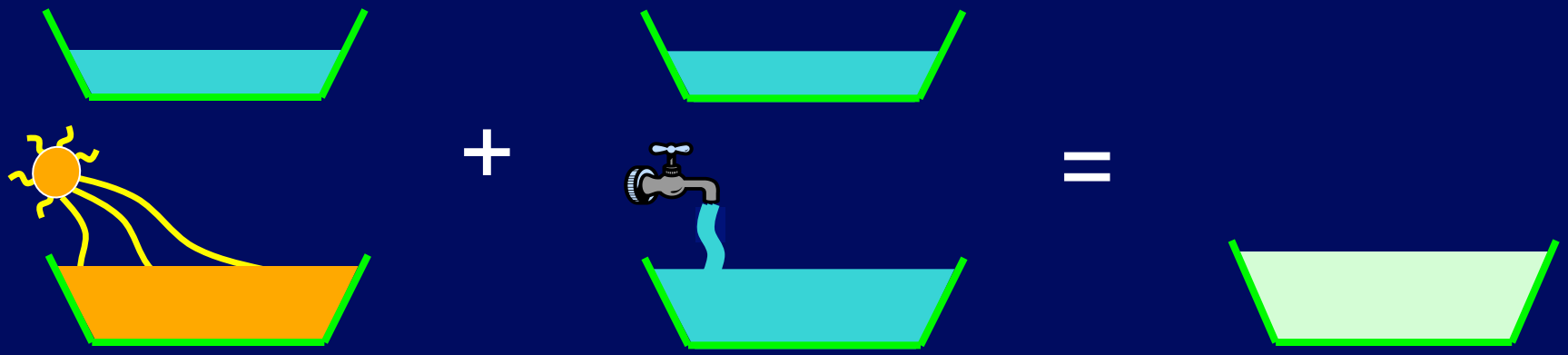


Global Sea Level Rise

addition of heat

addition of freshwater

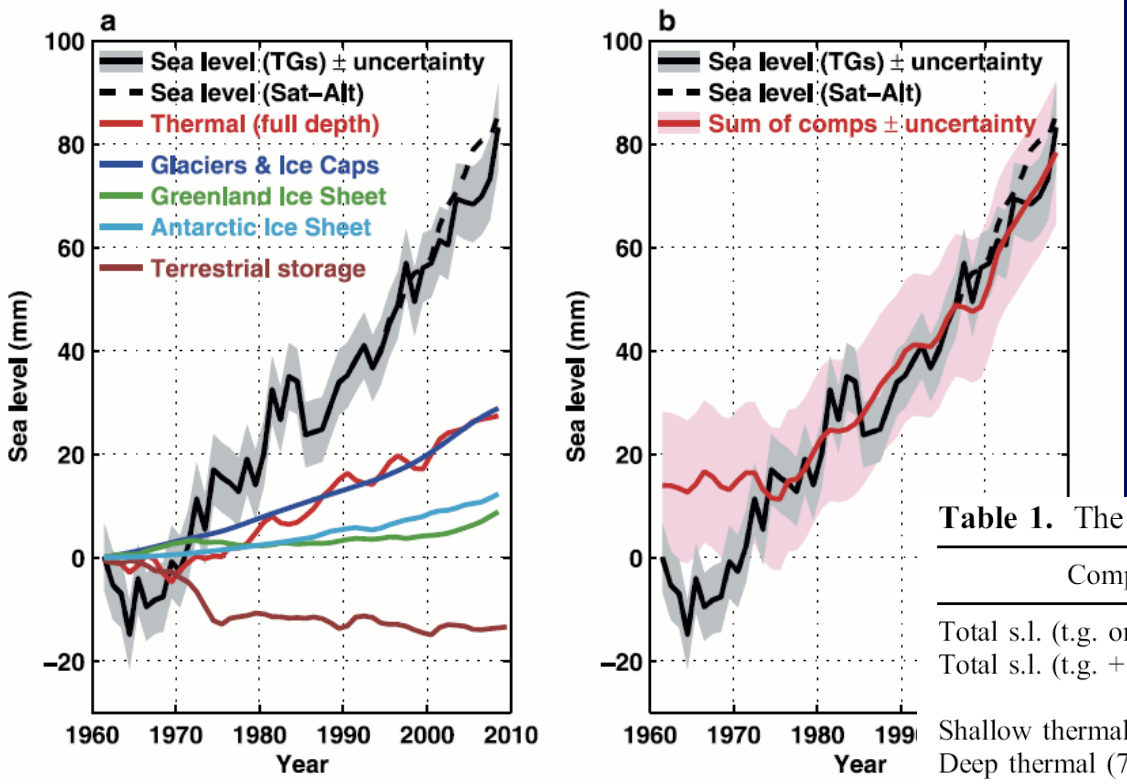
Total sea level rise



1/2 to 1/3 of total

5 mm of thermosteric sea level rise ≈ 3 x 10^{22} J of OHC

The Recent Sea Level Budget



mm/yr

Table 1. The Sea-Level Budget[a]

Component	1972 → 2008	1993 → 2008
Total s.l. (t.g. only)	**1.83 ± 0.18**[b]	**2.61 ± 0.55**
Total s.l. (t.g. + sat)	**2.10 ± 0.16**	**3.22 ± 0.41**
Shallow thermal (0–700m)	0.63 ± 0.09	0.71 ± 0.31
Deep thermal (700–3000m)	0.07 ± 0.10	0.07 ± 0.10
Abyssal thermal (3000m-bottom)	0.10 ± 0.06	0.10 ± 0.06
Total thermal (full depth)	**0.80 ± 0.15**	**0.88 ± 0.33**
Glaciers & Ice Caps	0.67 ± 0.03	0.99 ± 0.04
Greenland Ice Sheet	0.12 ± 0.17	0.31 ± 0.17
Antarctic Ice Sheet	0.30 ± 0.20	0.43 ± 0.20
Land ice (G&IC, GIS, AIS)	**1.09 ± 0.26**	**1.73 ± 0.27**
Thermal (full depth) + Land ice	**1.89 ± 0.30**	**2.61 ± 0.42**
Dam retention	−0.44 ± 0.15	−0.30 ± 0.15
Groundwater depletion	0.26 ± 0.07	0.35 ± 0.07
Natural terrestrial storage	0.07 ± 0.10	−0.14 ± 0.10
Total terrestrial storage	**−0.11 ± 0.19**	**−0.08 ± 0.19**
Total mass contributions	**0.98 ± 0.33**	**1.66 ± 0.33**
Total thermal + Mass	**1.78 ± 0.36**	**2.54 ± 0.46**
Residual (t.g. only)	**0.05 ± 0.40**	**0.08 ± 0.72**
Residual (t.g. + sat)	**0.32 ± 0.39**	**0.69 ± 0.62**

Good understanding of the causes of Sea Level Rise since ~1970

From Church et al., *GRL*, 2011

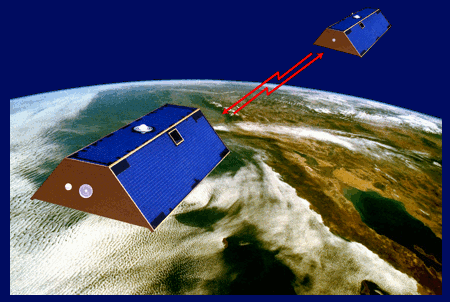
Measuring the World's Oceans

addition of heat

addition of freshwater

Total sea level rise

+



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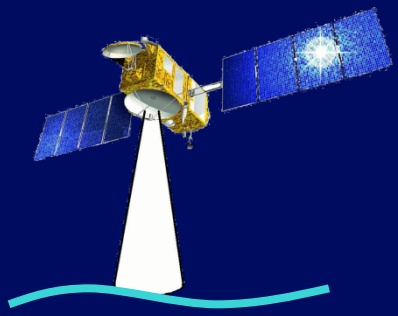
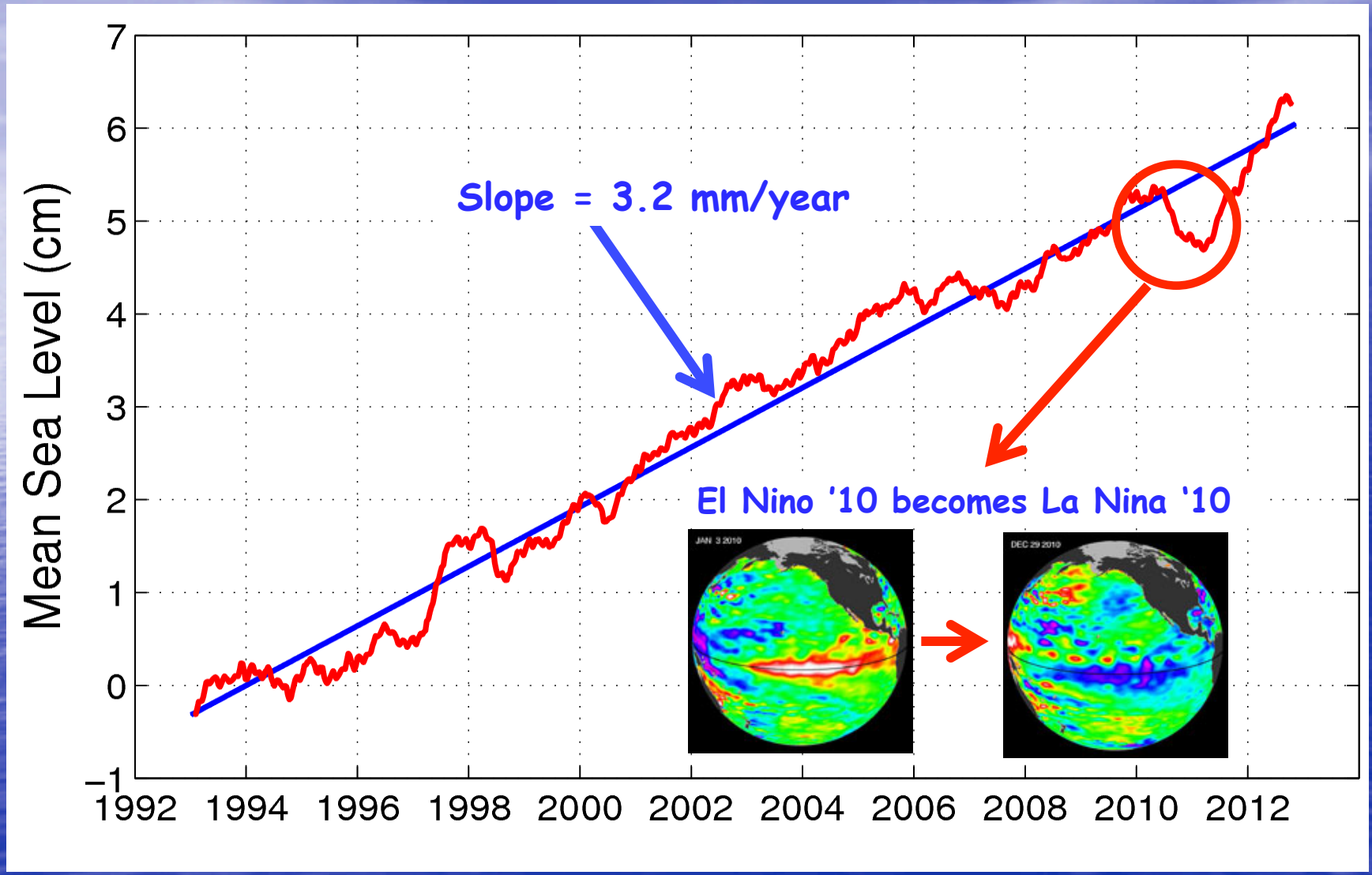


Argo

GRACE

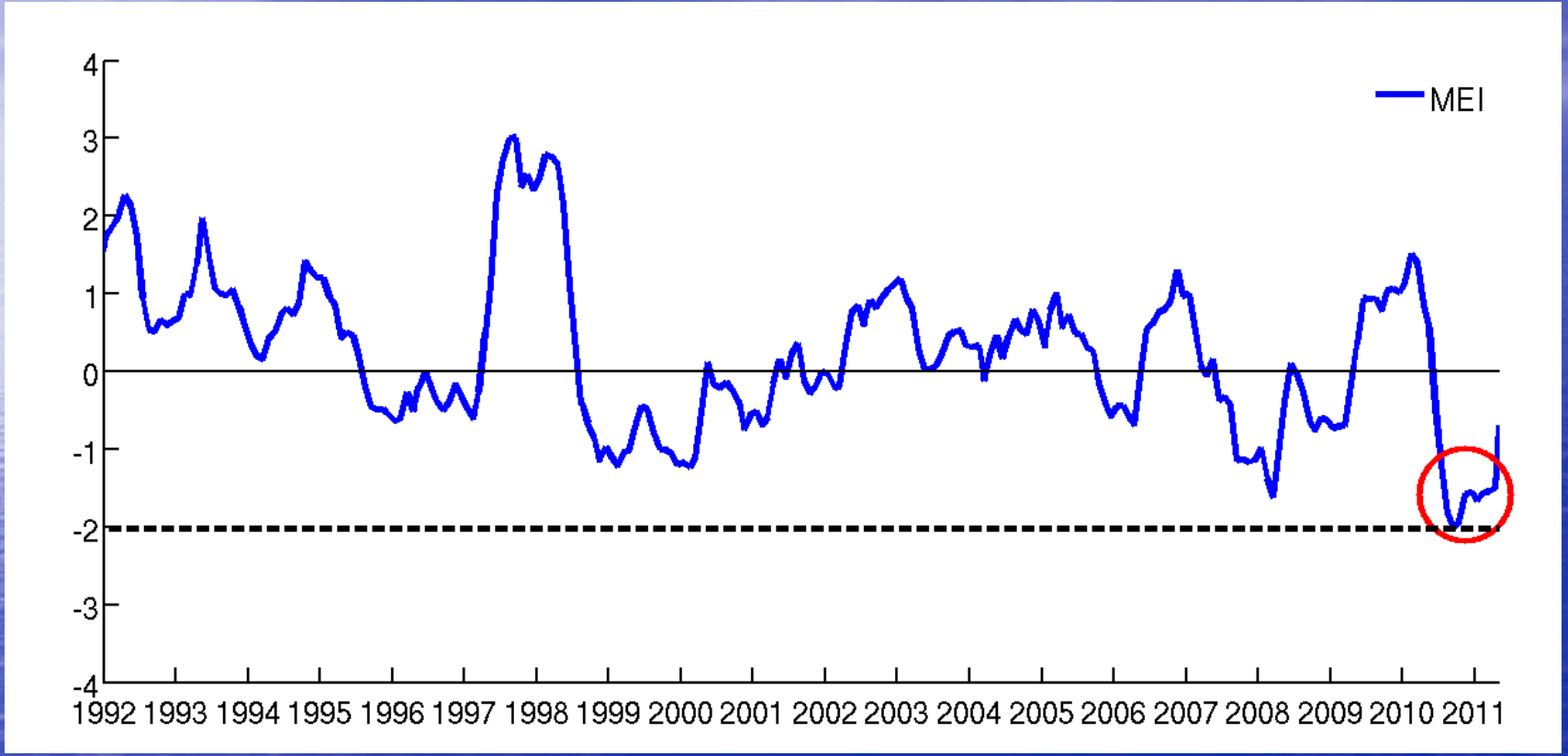
Jason

Global Sea Level Drops 5 mm in 2010



From Boening et al., *GRL*, 2012

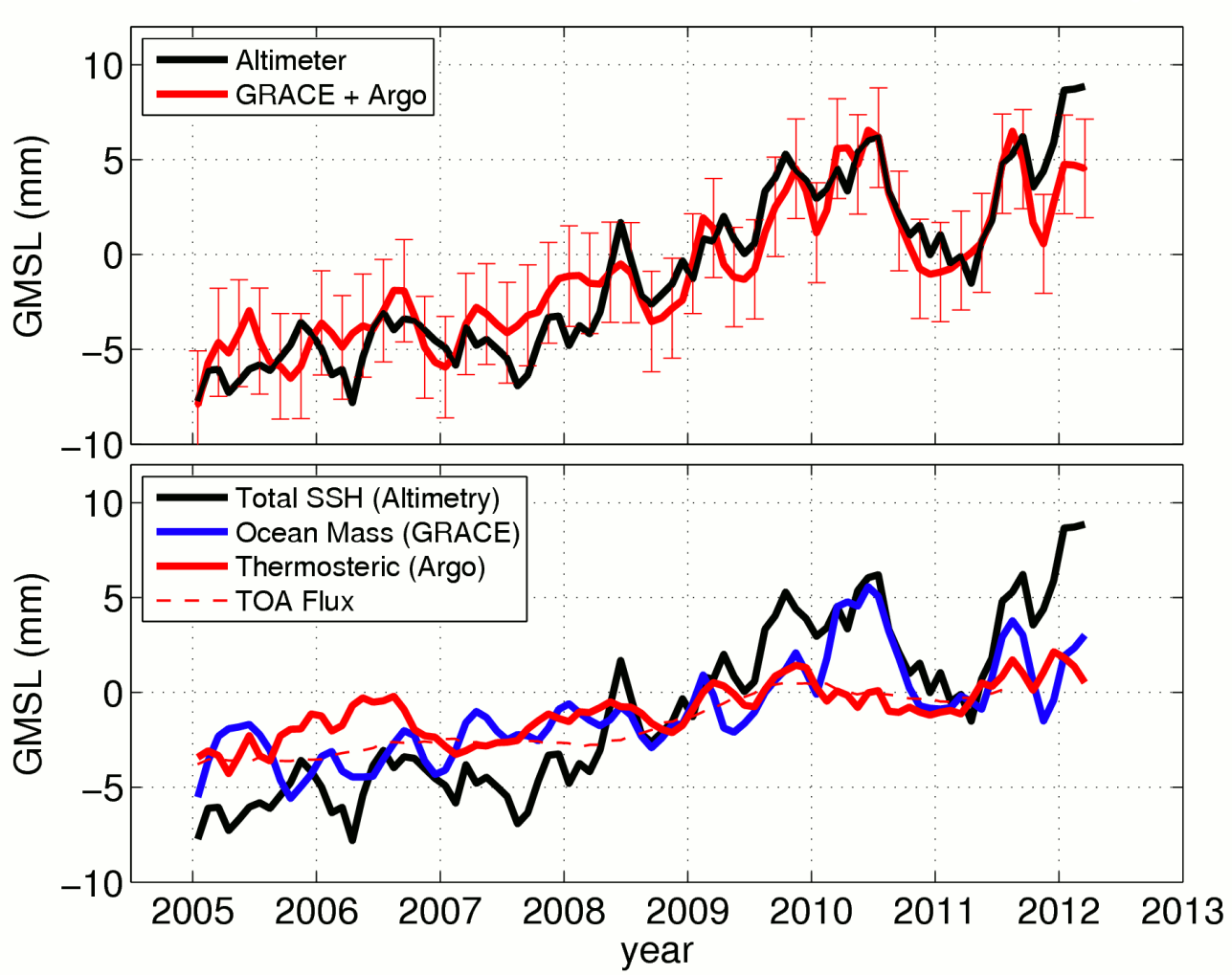
2010 and the Big La Niña



2010 brought a transition from a moderate El Niño to a strong La Niña

From Boening et al., *GRL*, 2012

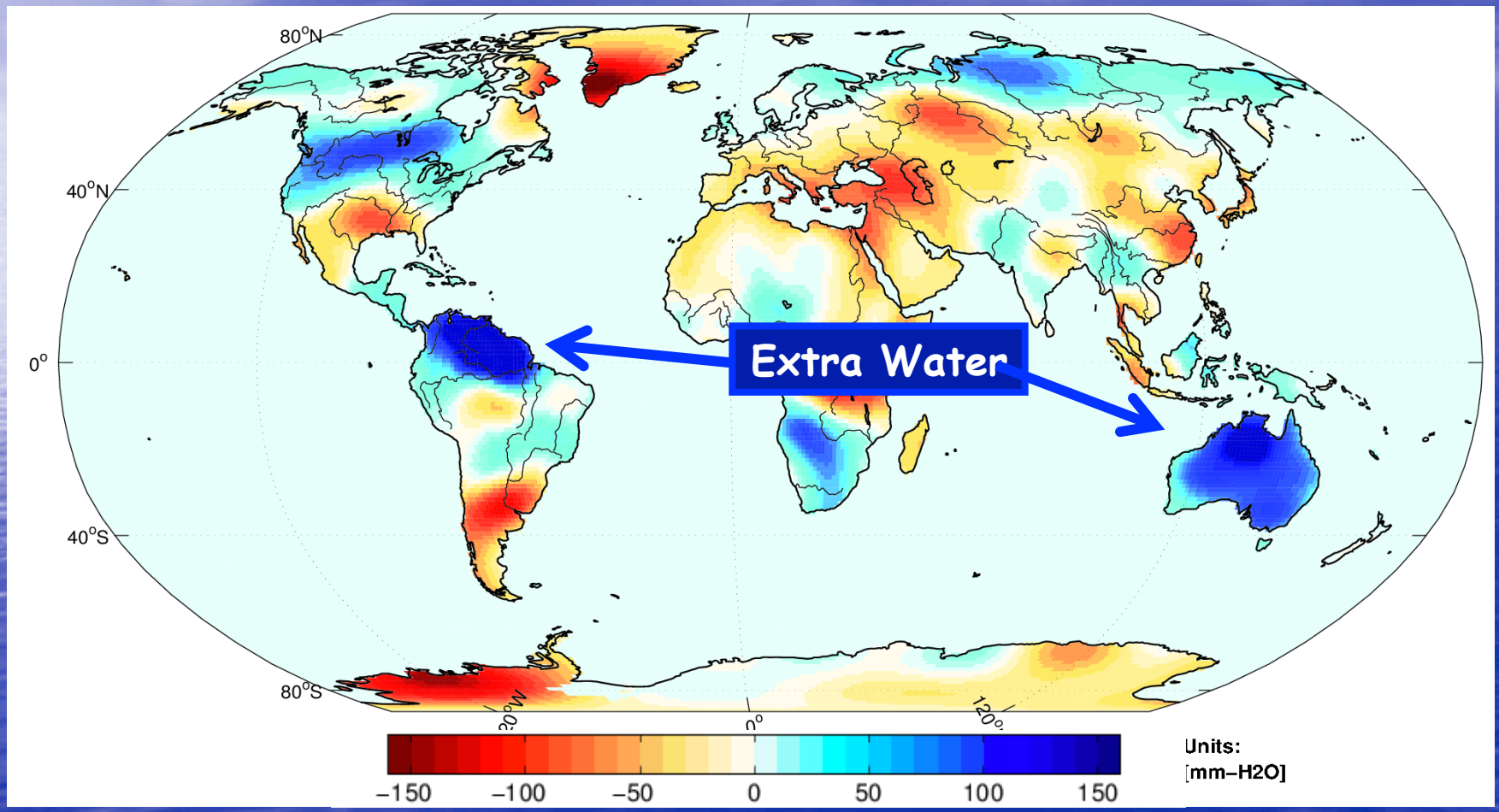
Closing the Sea Level Budget during the 2010 drop



Thermal Expansion from Argo and Ocean Mass from GRACE explain drop in sea level from altimetry Ocean Mass is the primary cause of the 2010-11 drop

From Boening et al., *GRL*, 2012

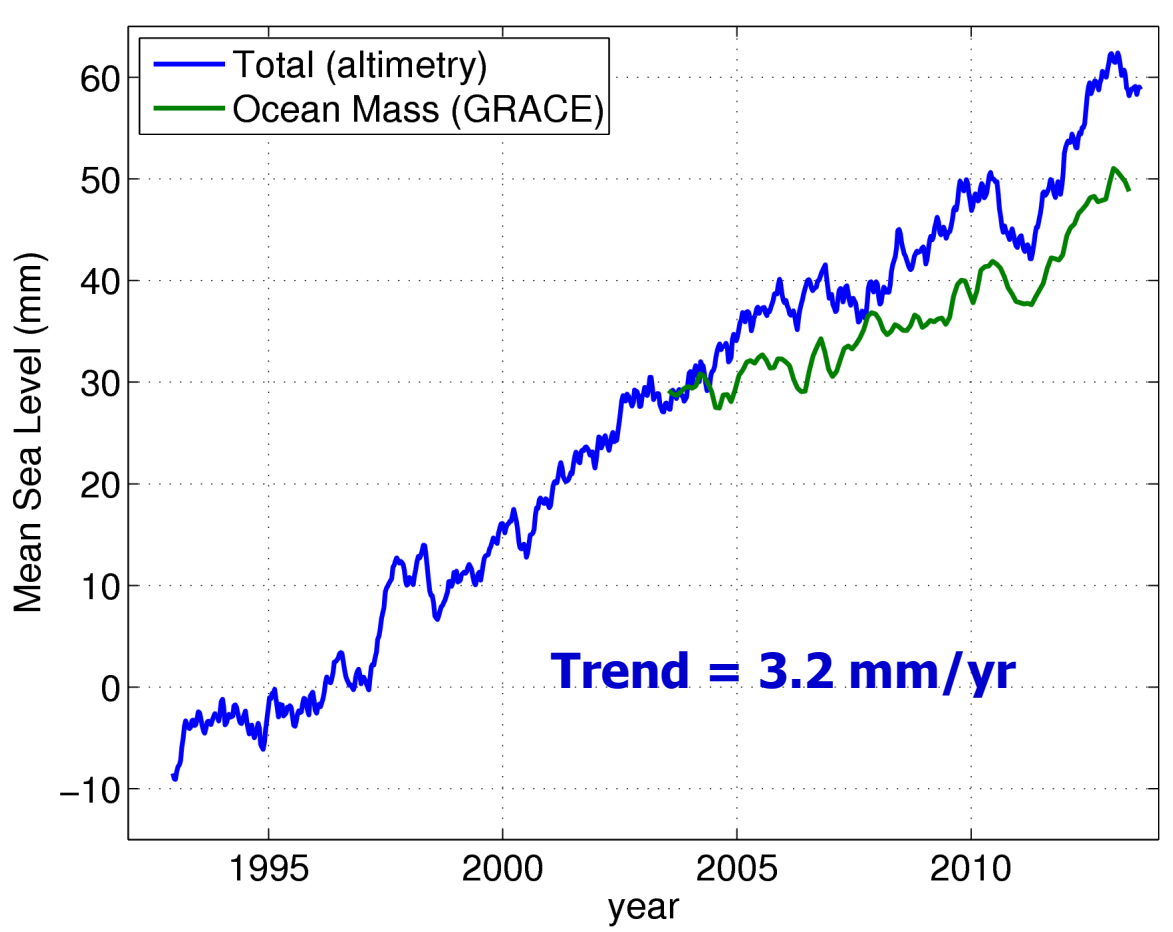
GRACE shows change in water from March 2010 to March 2011



Mass in centimeters of water thickness

From Boening et al., *GRL*, 2012

Satellite Sea Level Obs



Difference can be used to infer ocean warming (and energy imbalance) independent of Argo

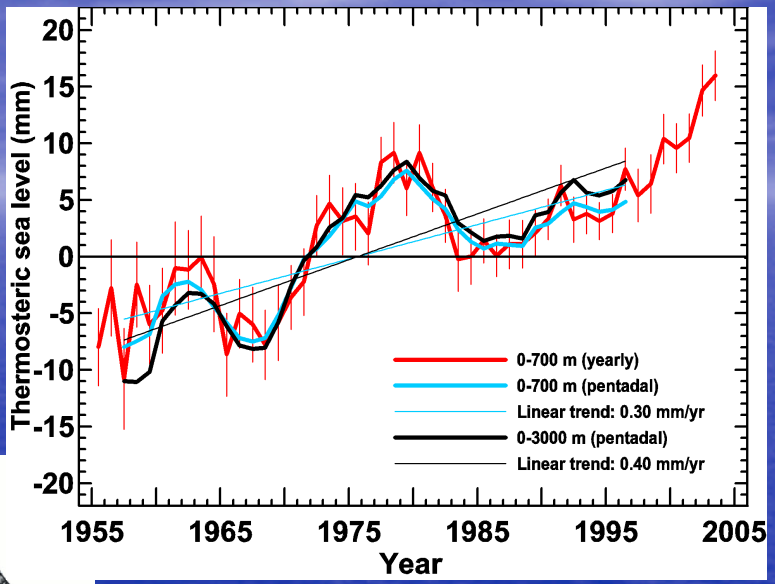
Sea Level data from http://sealevel.colorado.edu

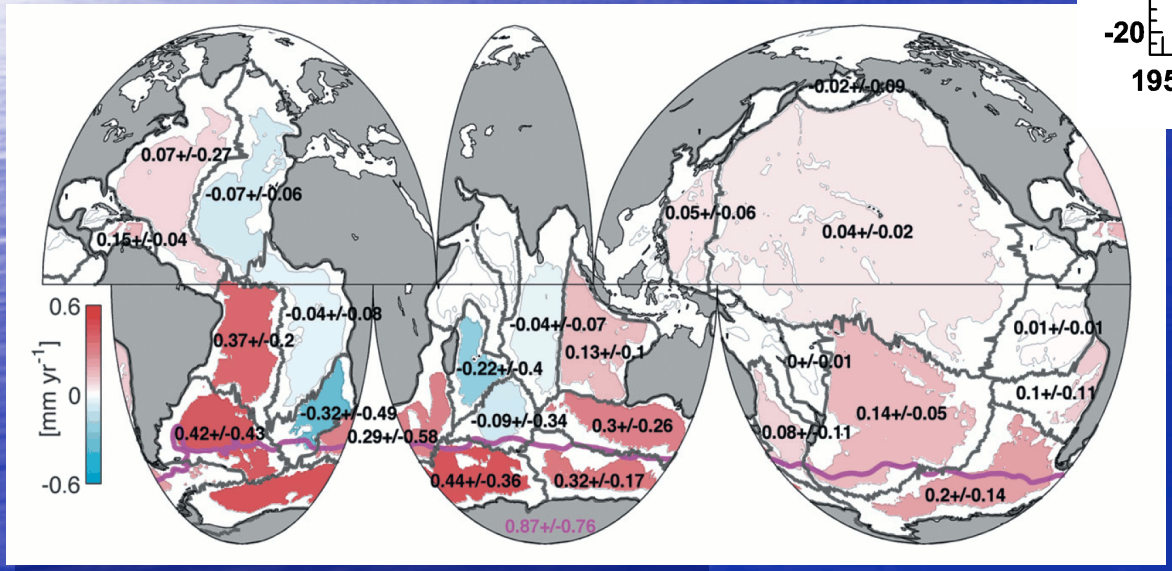
Ocean mass (F. Landerer, pers. comm.)

Deep Warming

700 – 3000 m:
0.07 mm/yr

Antonov et al., GRL, 2005



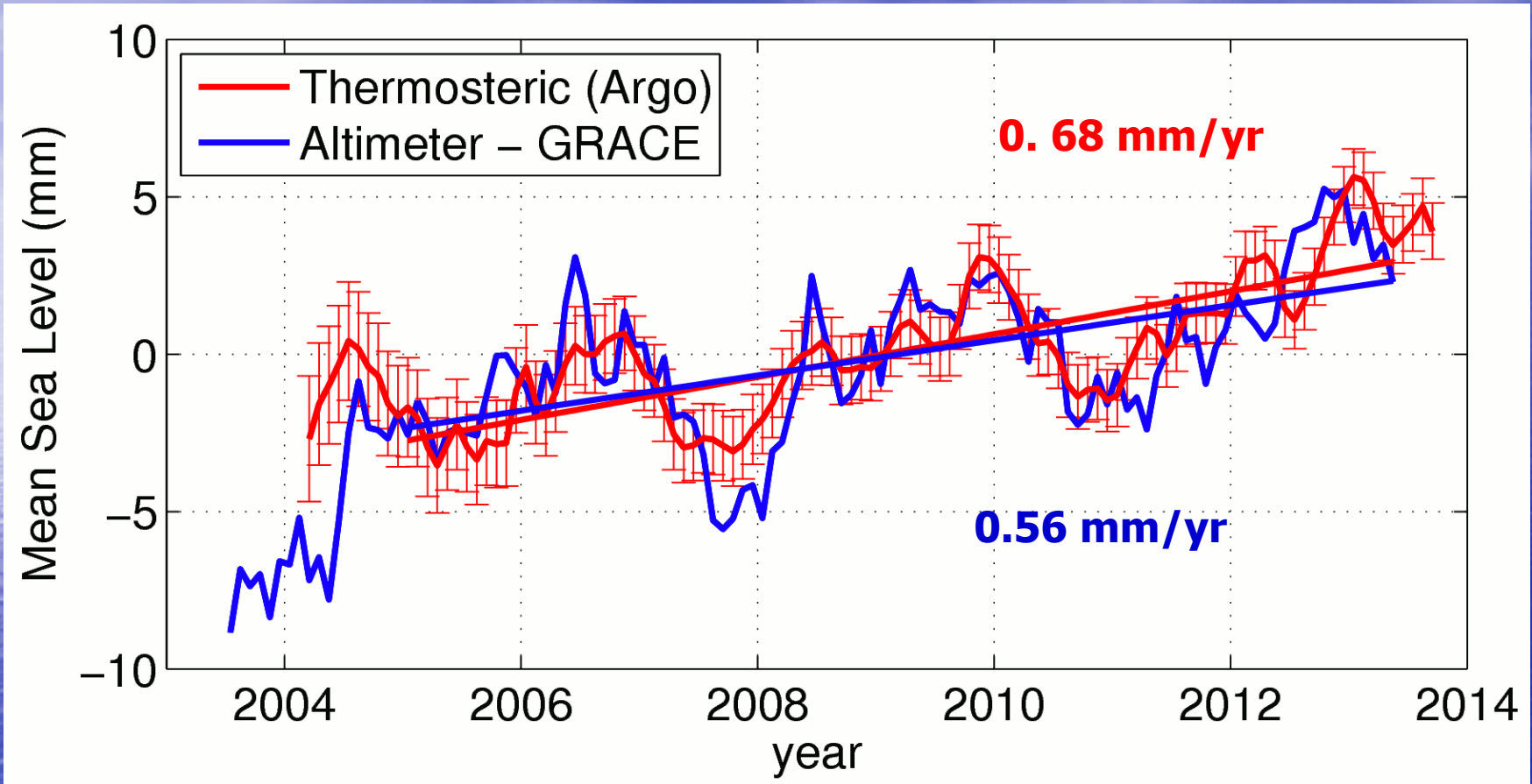


Below 3000 m: 0.1 mm/yr

Purkey & Johnson, *J. Climate*, 2010

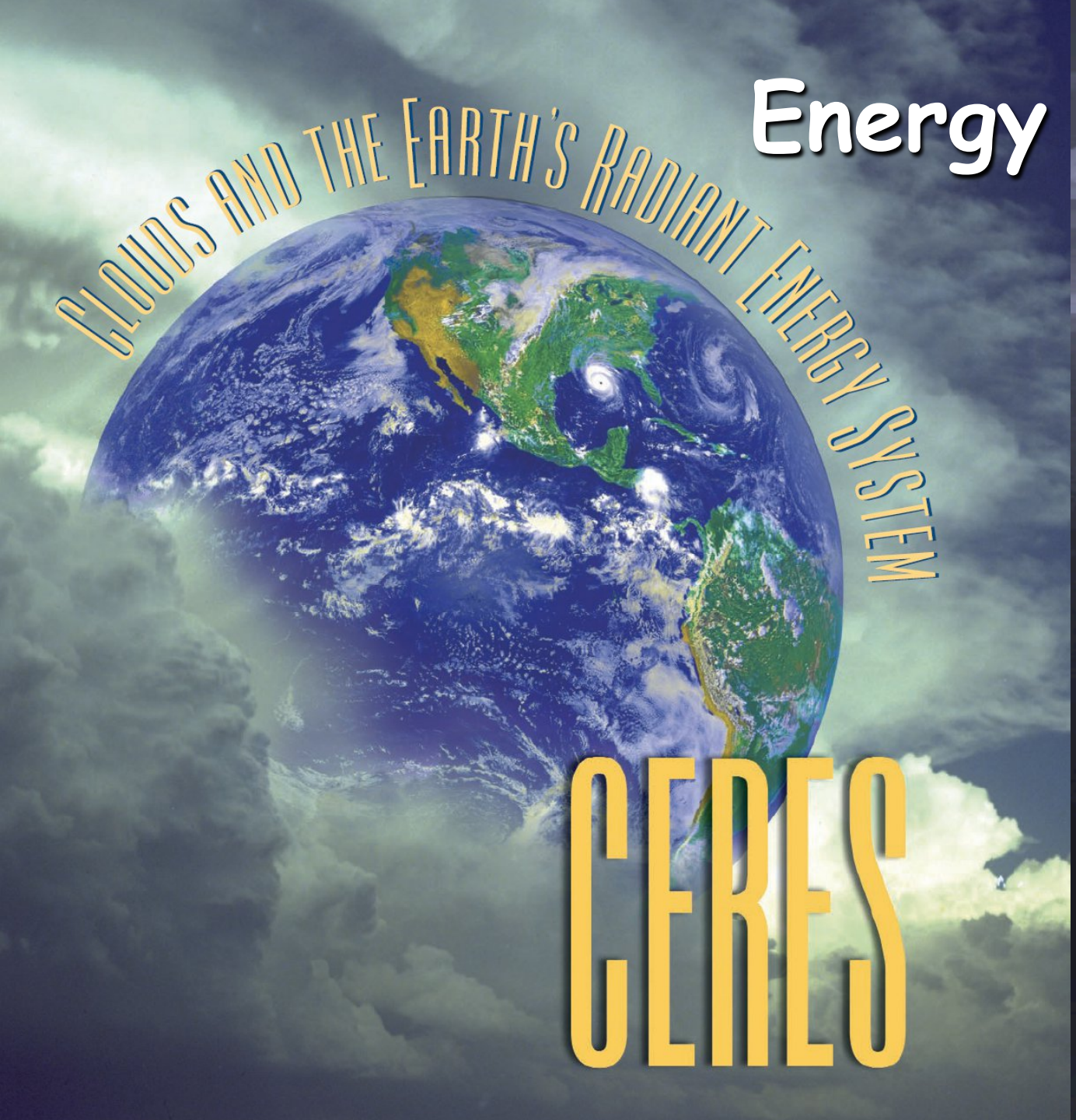
Total deep warming:
0.17 mm/yr
= 0.14 W/m^2

The Sea Level Budget

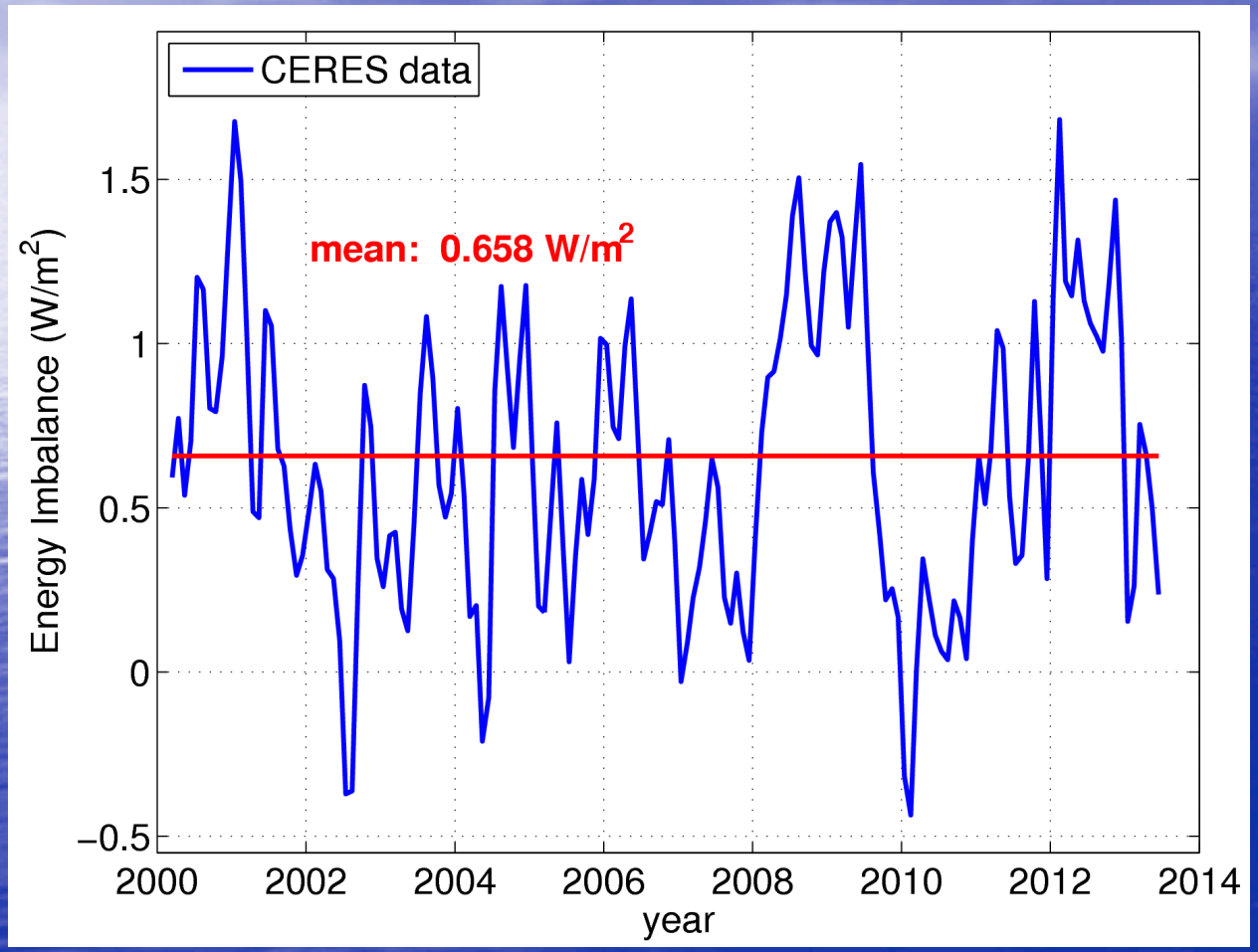


Includes 0.17 mm/yr trend from deep ocean (>than 700) m as in Church et al. (2011)

Energy Balance

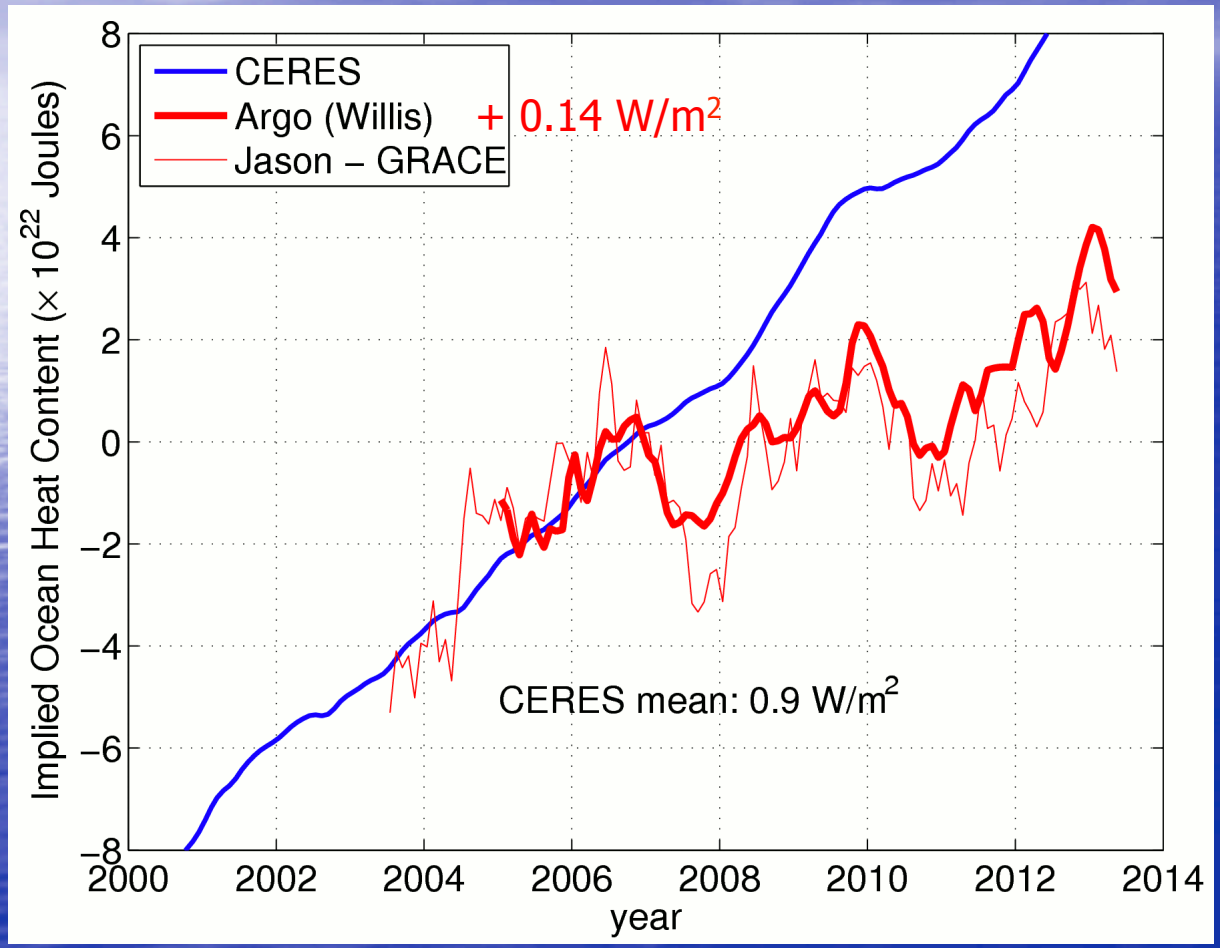


Energy Balance CERES Satellite



Time mean imbalance estimated from comparison with Lyman et al. (2010)

Energy Balance Satellite vs. In Situ

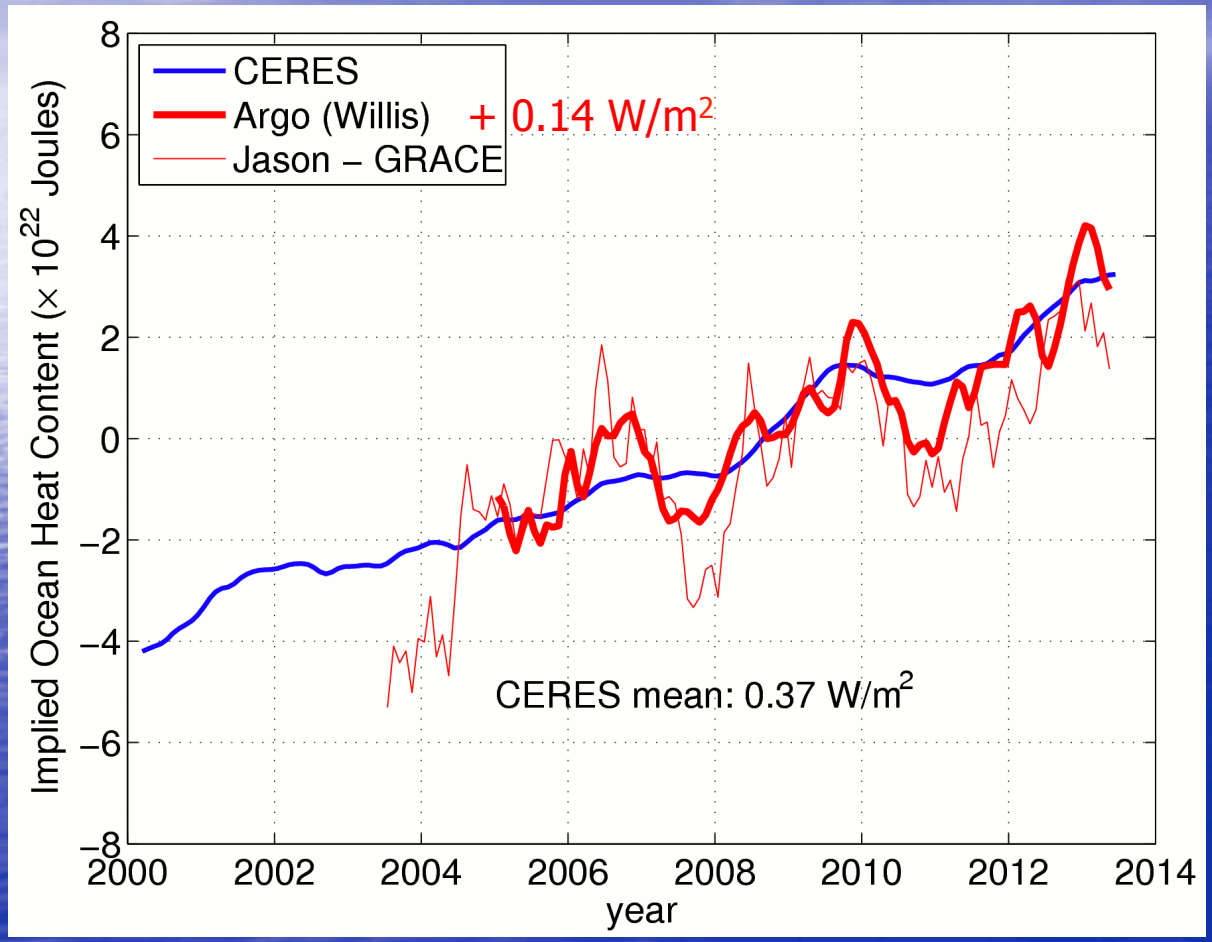


0.14 W/m^2 for deep ocean (Church et al., 2011)

Assumption of 0.9 W/m^2 imbalance suggested by Trenberth & Fasullo seems to contradict inferred and direct estimates of ocean warming

Assume 5 mm of thermosteric SL = 3 x 10^{22} J

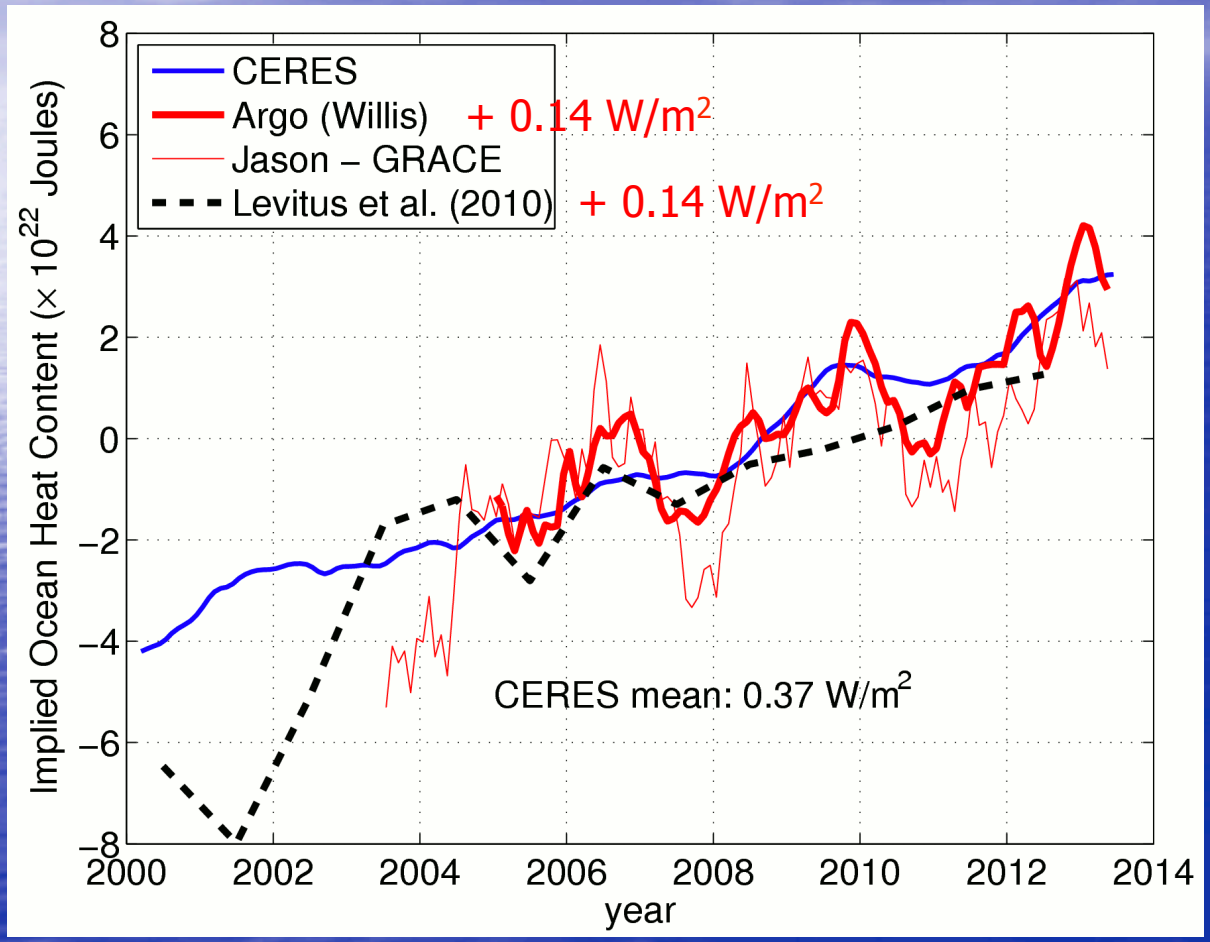
Energy Balance Satellite vs. In Situ



Fitting the entire Argo period suggest imbalance of 0.32 W/m^2

Divergence with pre-Argo inferred estimate

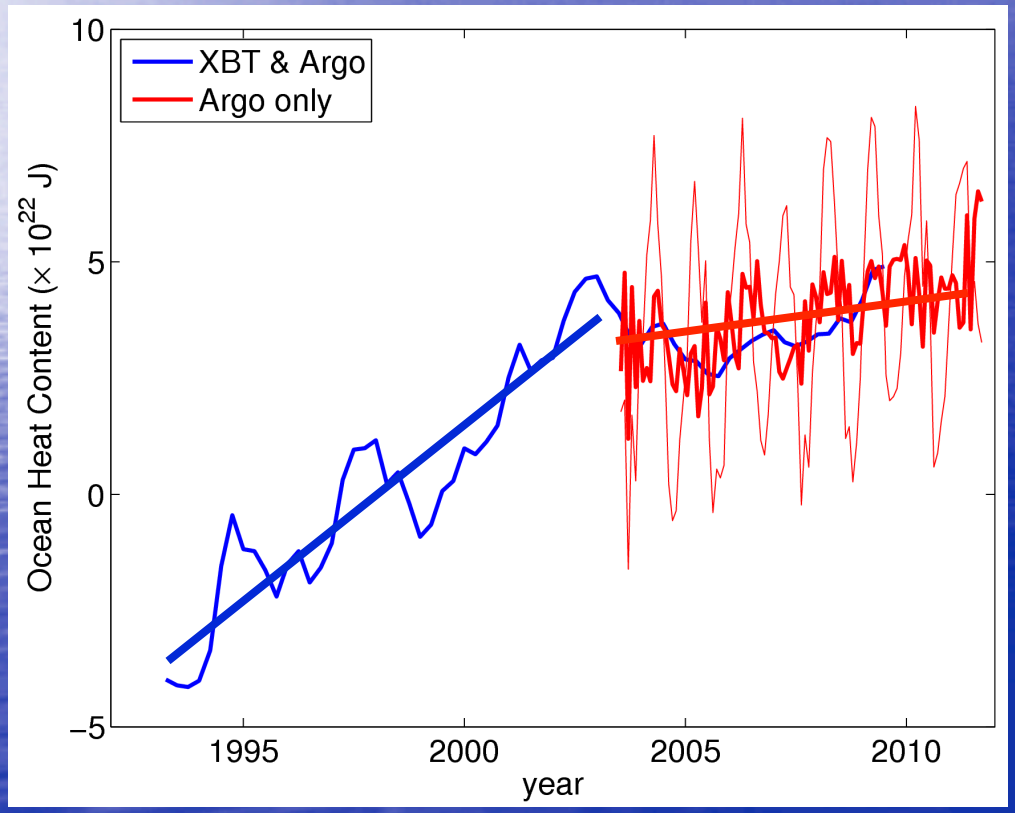
Energy Balance Satellite vs. In Situ



Inclusion of bias-corrected XBT data does not necessarily shed any light on discrepancy in early record

What about the "slowdown"?

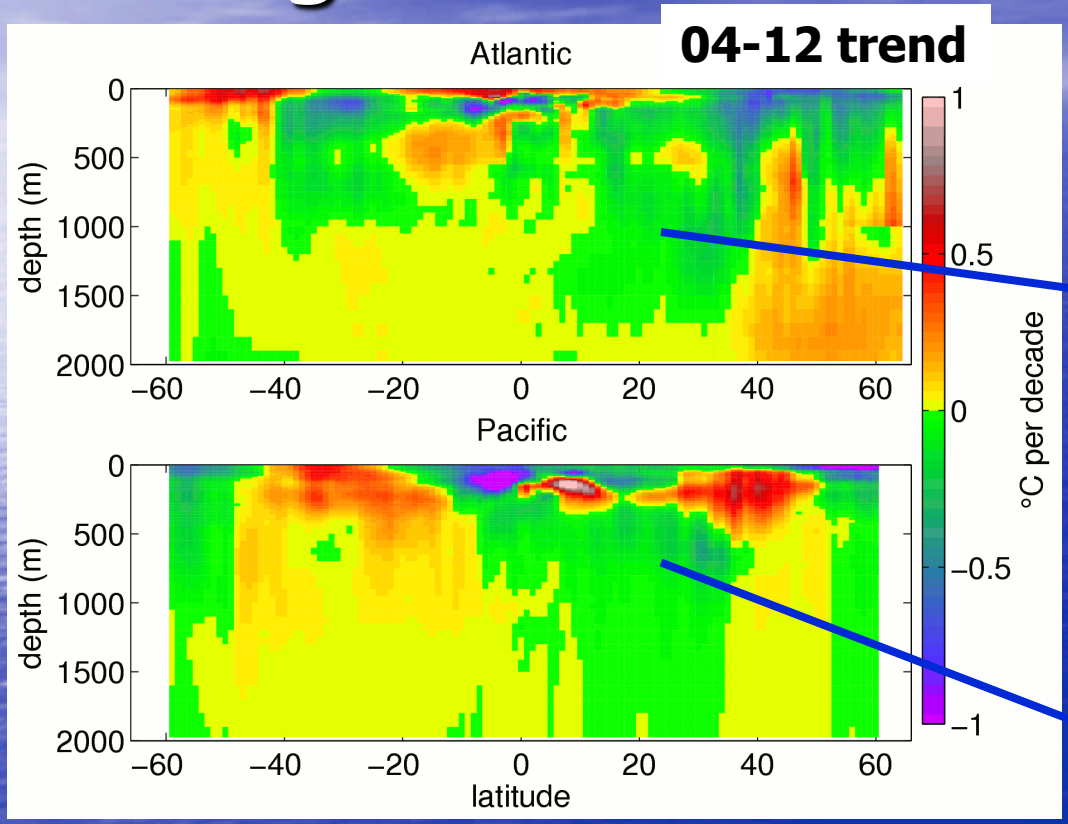
0-750 m Ocean Heat Content

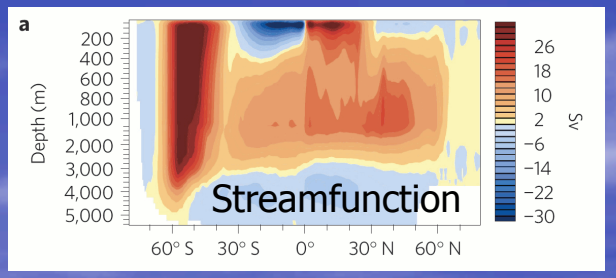


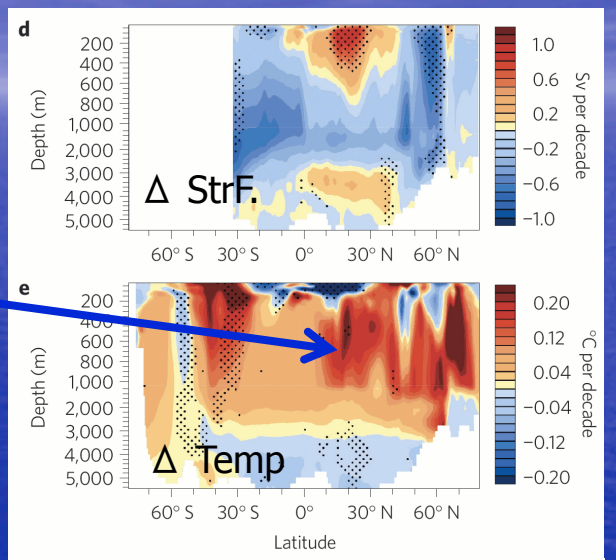
Bias-corrected XBTs included in estimate since 1993

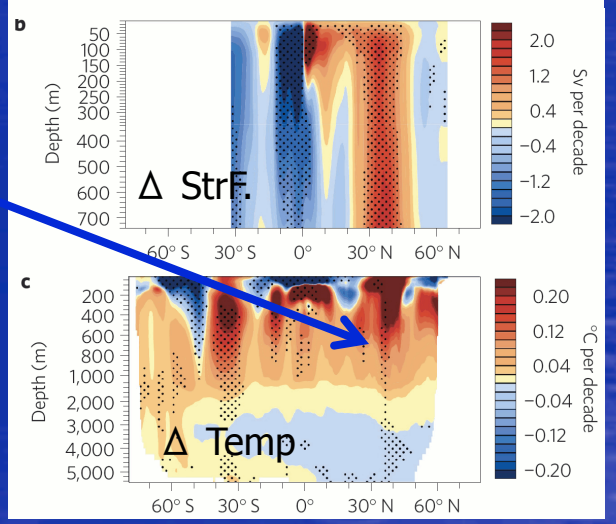
Was there a slowdown in ocean warming during the 2000s?

Warming trends during the 2000s









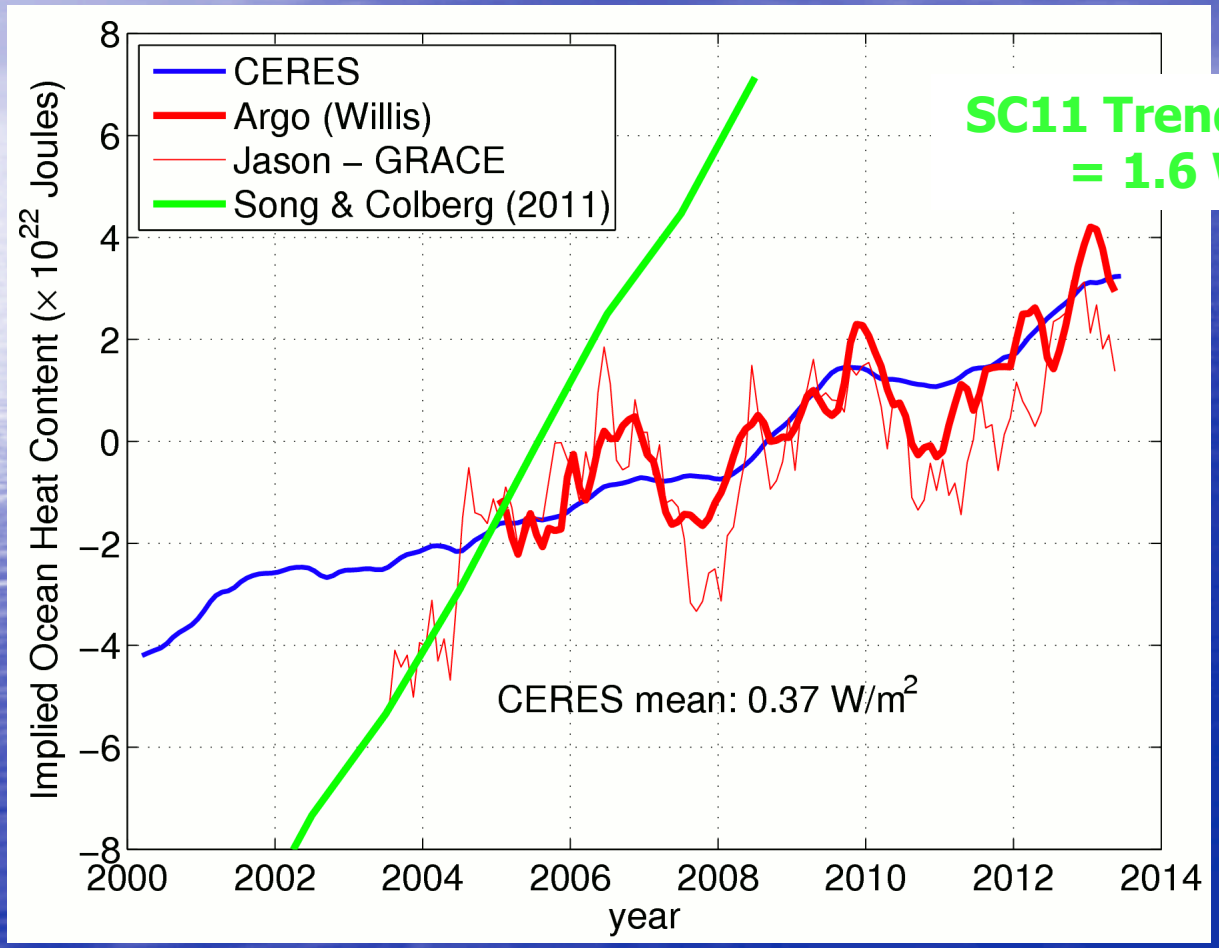
Global

Atlantic

Pacific

Upper & mid-depth temp. changes are wrong sign to be explained by Meehl et al., *Nat. Clim. Ch.*, 2011

Energy Balance
Satellite vs. In Situ & Model

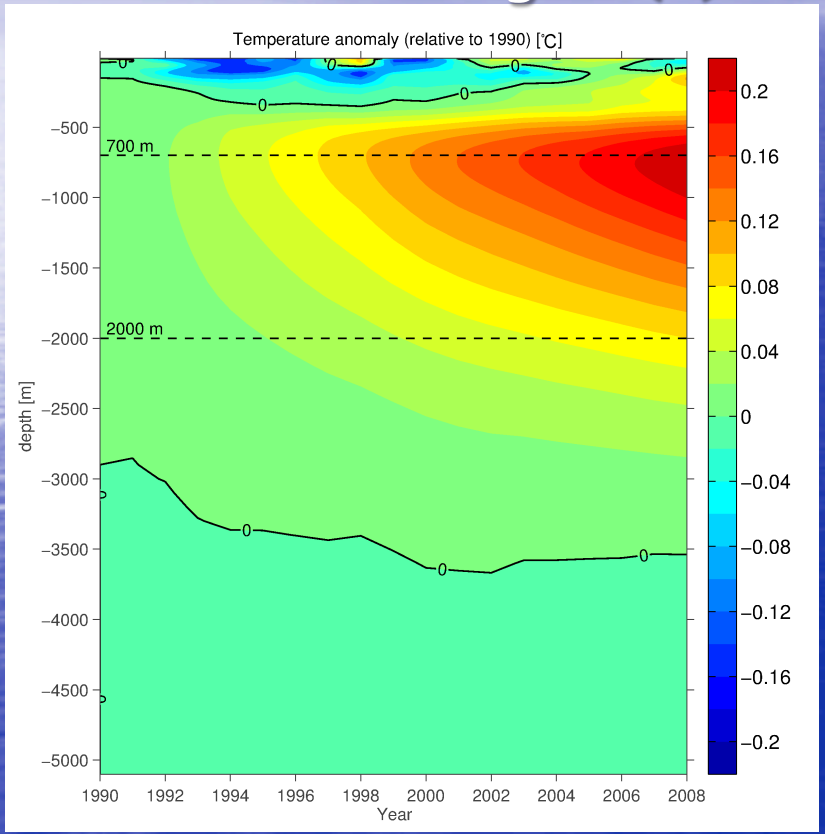


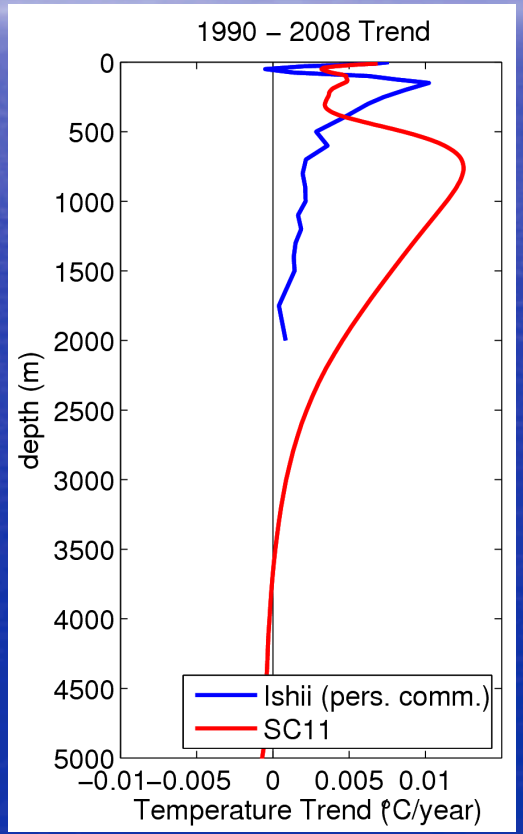
SC11 Trend ('93-08) = 1.6 W/m²

Recent model results suggest very large amounts of deep warming (equal to 1.1 mm/yr of steric height *below* 700 m, or 1.1 W/m²)

Deep Warming – Ocean Model

Global average T(z)





Model suggests rapid warming at base of thermocline

Vertical diffusion?

Song & Colbert (2011)

Conclusions (1 of 2)

- Ocean warming is a proxy for radiation imbalance
- Inferred estimate from Jason & GRACE in good agreement with Argo after 2005
- Satellite & in situ observations suggest radiative imbalance ~ 0.3 to 0.6 W/m^2
- Biases & magnitude of deep warming complicate energy balance pre-Argo
- Interannual to decadal variability in TOA remains open question

Conclusions (2 of 2)

- Global Mean Sea Level fell by about 5 mm between 2010 and 2011
- Most of the drop was due to transfer of water from ocean to land
- Sea Level Rise is likely to resume in the next year (*depending* on La Niña)